

CS660: Intro to Database Systems

Class 7: Tree-Structured Indexing

Instructor: Manos Athanassoulis

<https://bu-disc.github.io/CS660/>

Tree-structured indexing

Intro & B⁺-Tree

Insert into a B⁺-Tree

Delete from a B⁺-Tree

Prefix Key Compression & Bulk Loading

Introduction

Recall: 3 alternatives for data entries k^ :*

- $\langle k, \text{entire data record} \rangle$
- $\langle k, \text{rid of data record with search key value } k \rangle$
- $\langle k, \text{list of rids of data records with search key } k \rangle$

Choice is orthogonal to the *indexing technique* used to locate data entries k^* .

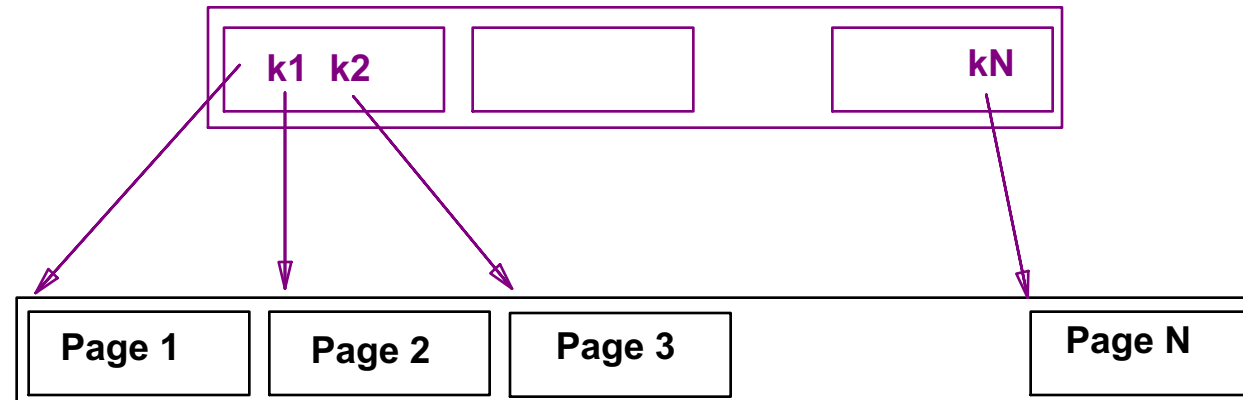
Tree-structured indexing techniques support both *range searches* and *equality searches*.

Range Searches

“Find all students with $gpa > 3.0$ ”

- If data is in sorted file, do **binary search** to find first such student, then **scan** to find others.
- Cost of **maintaining sorted file** + **performing binary search** in a database can be quite high.

Simple idea: Create an “index” file.



Can do binary search on a (smaller) index file!



Index File



what can we do?

Data File

B+ Tree: The Most Widely-Used Index

Insert/delete at $\log_F(N)$ cost; keep tree *height-balanced*.

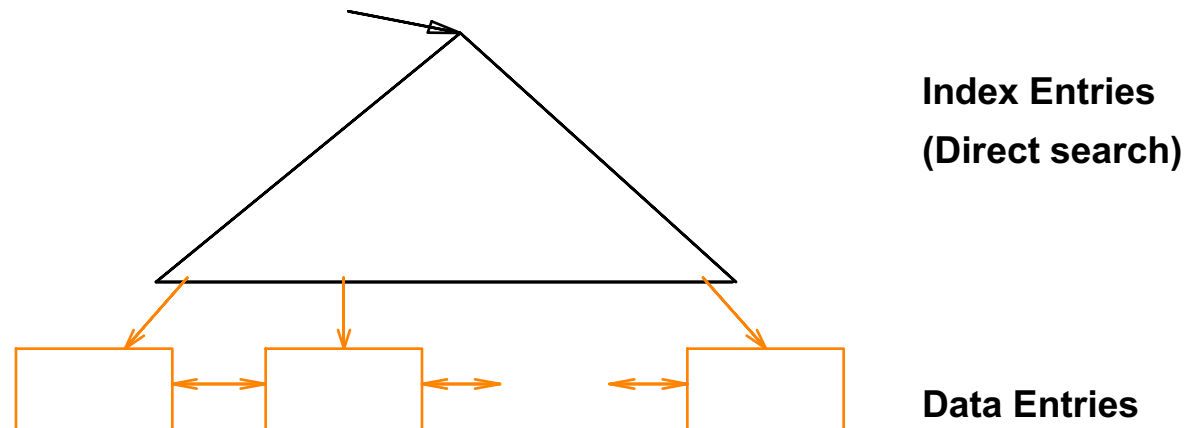
(F = fanout, N = # leaf pages)

Minimum 50% occupancy (except for root).

Each node contains $d \leq m \leq 2d$ entries. “ d ” is called the *order* of the tree.

Supports equality and range-searches efficiently.

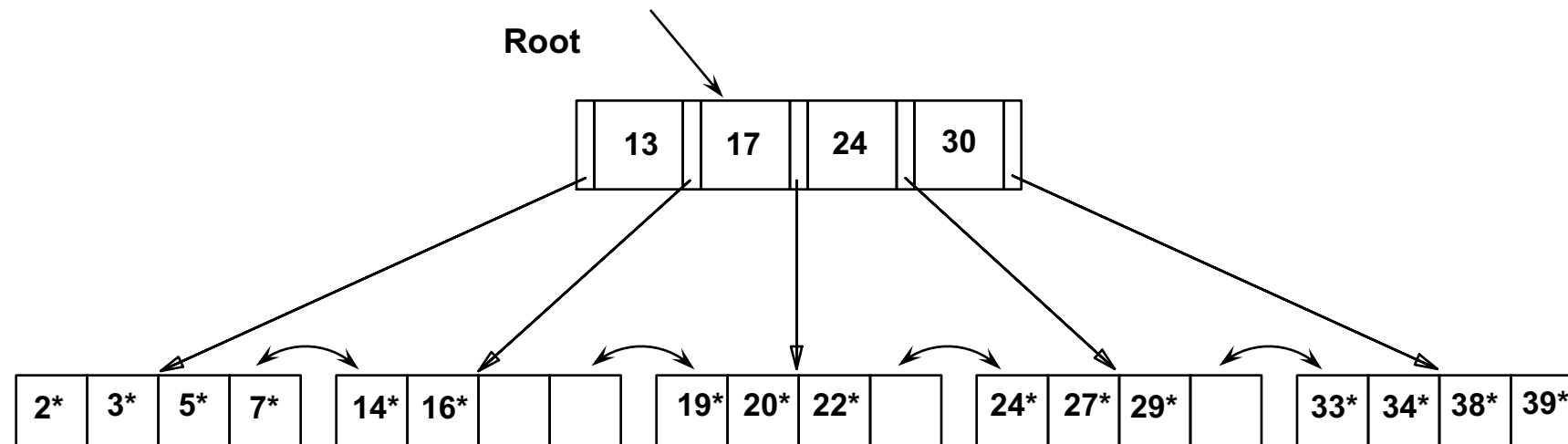
All searches go from root to leaves, in a dynamic structure.



Example B+ Tree

Search begins at root, and key comparisons direct it to a leaf.

Search for 5^* , 15^* , all data entries $\geq 24^*$...



➡ Based on the search for 15^* , we know it is not in the tree!

B+ Trees in Practice (cool facts!)

Typical order: 100. Typical fill-factor: 67%.

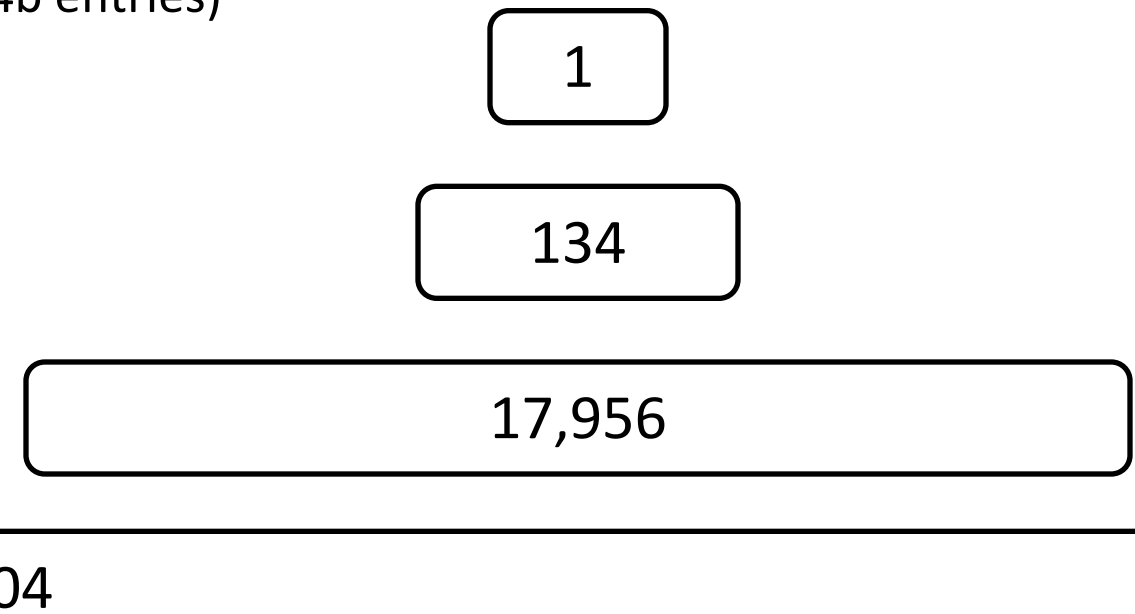
- average fanout = $2 \cdot 100 \cdot 0.67 = 134$

Typical capacities:

- Height 3: $133^3 = 2,406,104$ entries
- Height 4: $133^4 = 312,900,721$ entries (19GB for 64b entries)

Can often hold top levels in buffer pool:

- Level 1 = 1 page = 8 KB
- Level 2 = 134 pages = 1 MB
- Level 3 = 17,956 pages = 140 MB
- Level 4 = 2,406,104 pages = 9 GB



Tree-structured indexing

Intro & B⁺-Tree

Insert into a B⁺-Tree

Delete from a B⁺-Tree

Prefix Key Compression & Bulk Loading

Inserting a Data Entry into a B+ Tree

Find correct leaf L .

Put data entry onto L .

- If L has enough space, *done!*
- Else, must split L (into L and a new node $L2$)
 - Redistribute entries evenly, copy up middle key.
 - Insert index entry pointing to $L2$ into parent of L .

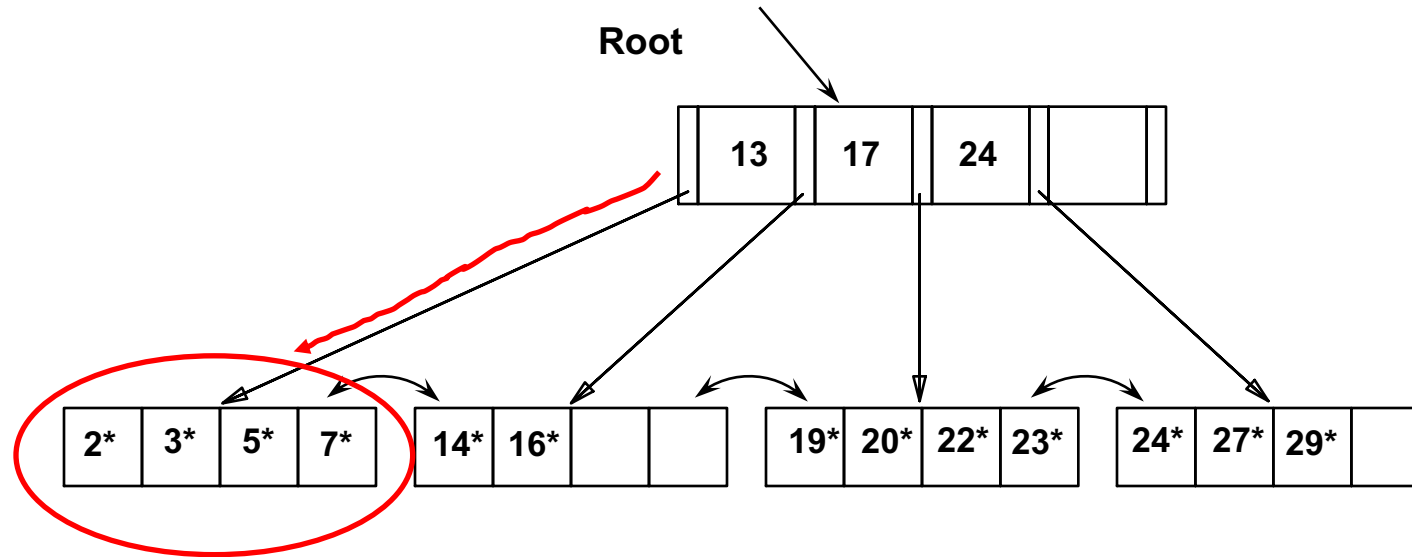
This can happen recursively

- To split index node, redistribute entries evenly, but push up middle key.
(Contrast with leaf splits.)

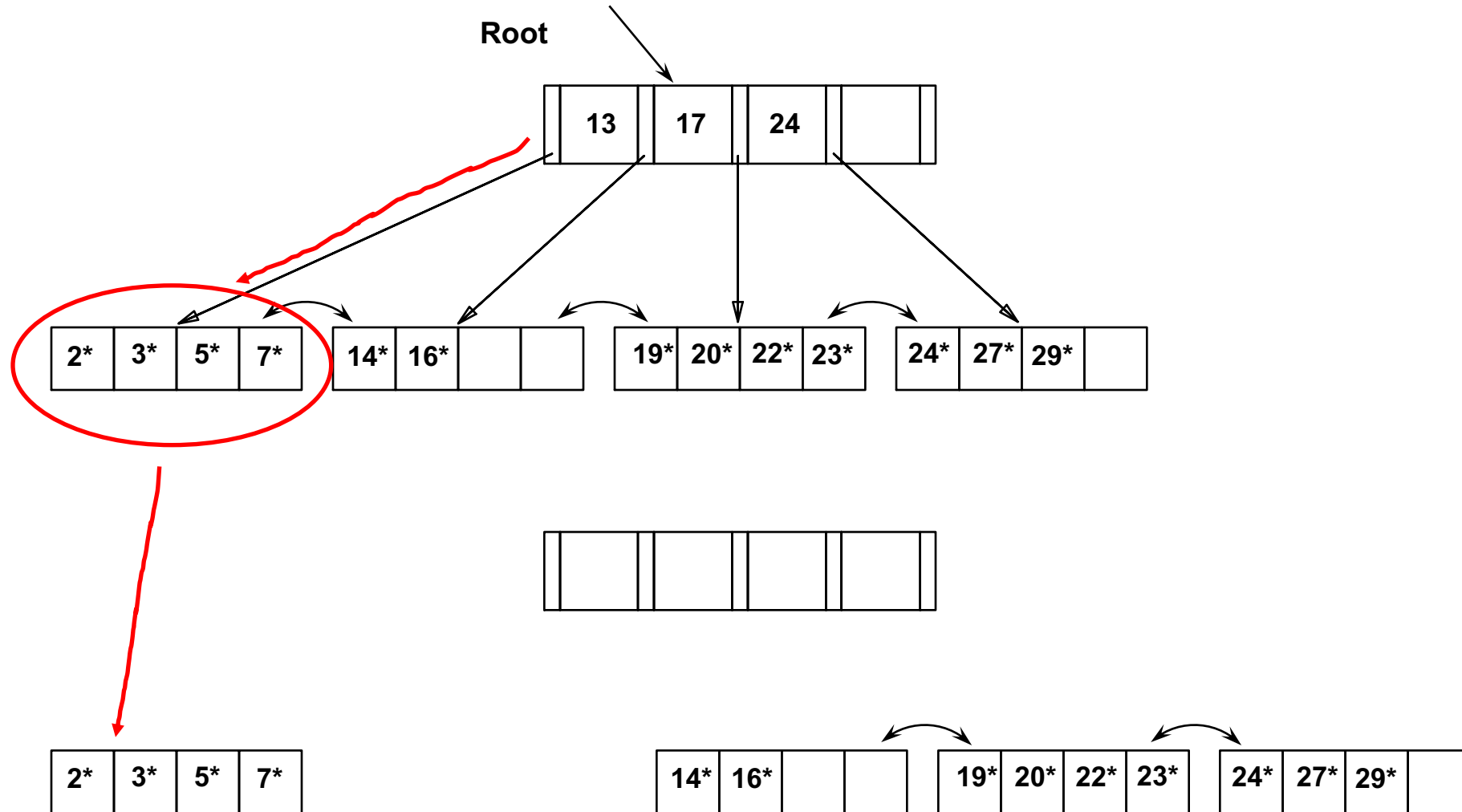
Splits “grow” tree; root split increases height.

- Tree growth: gets wider or one level taller at top.

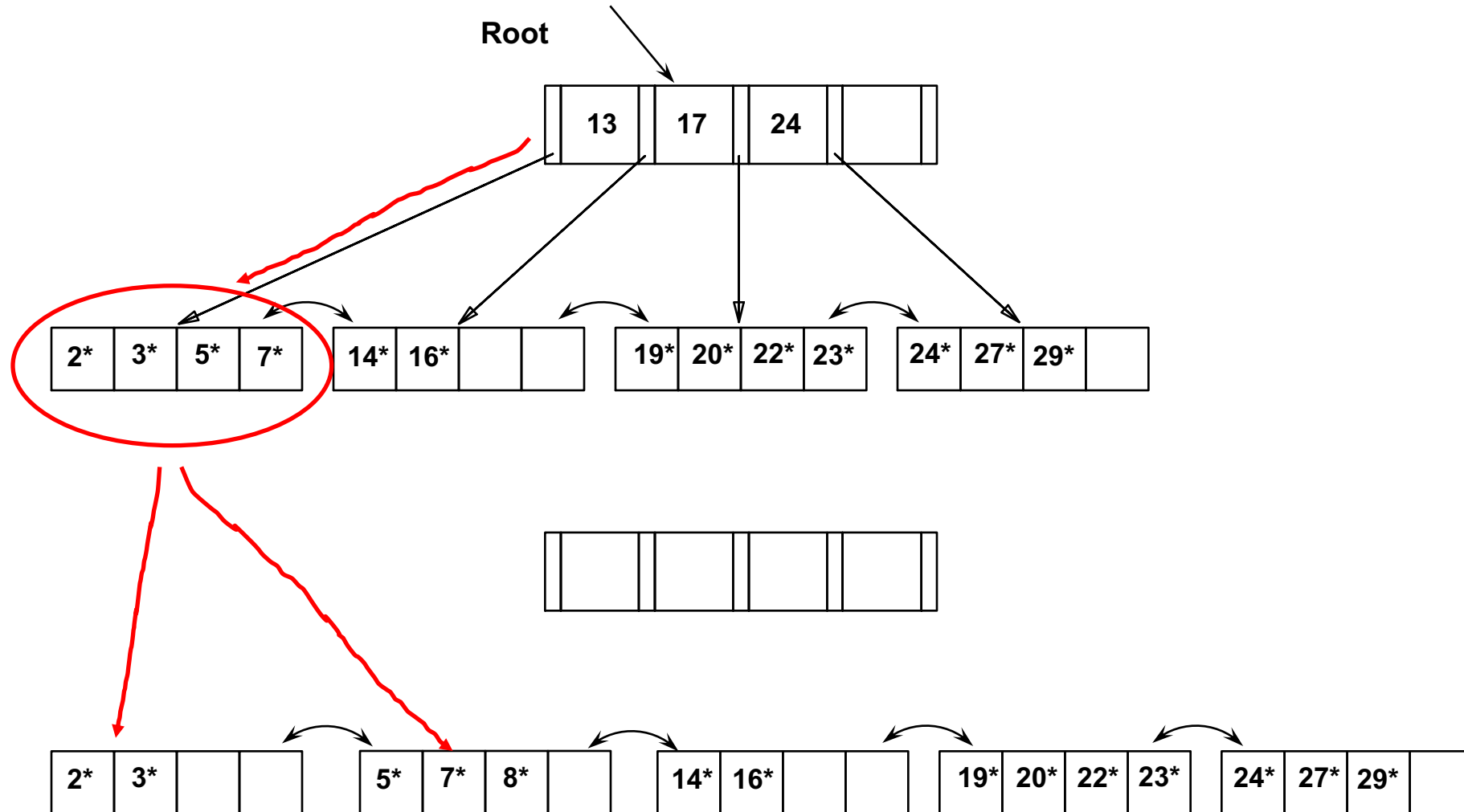
Example B+ Tree - Inserting 8*



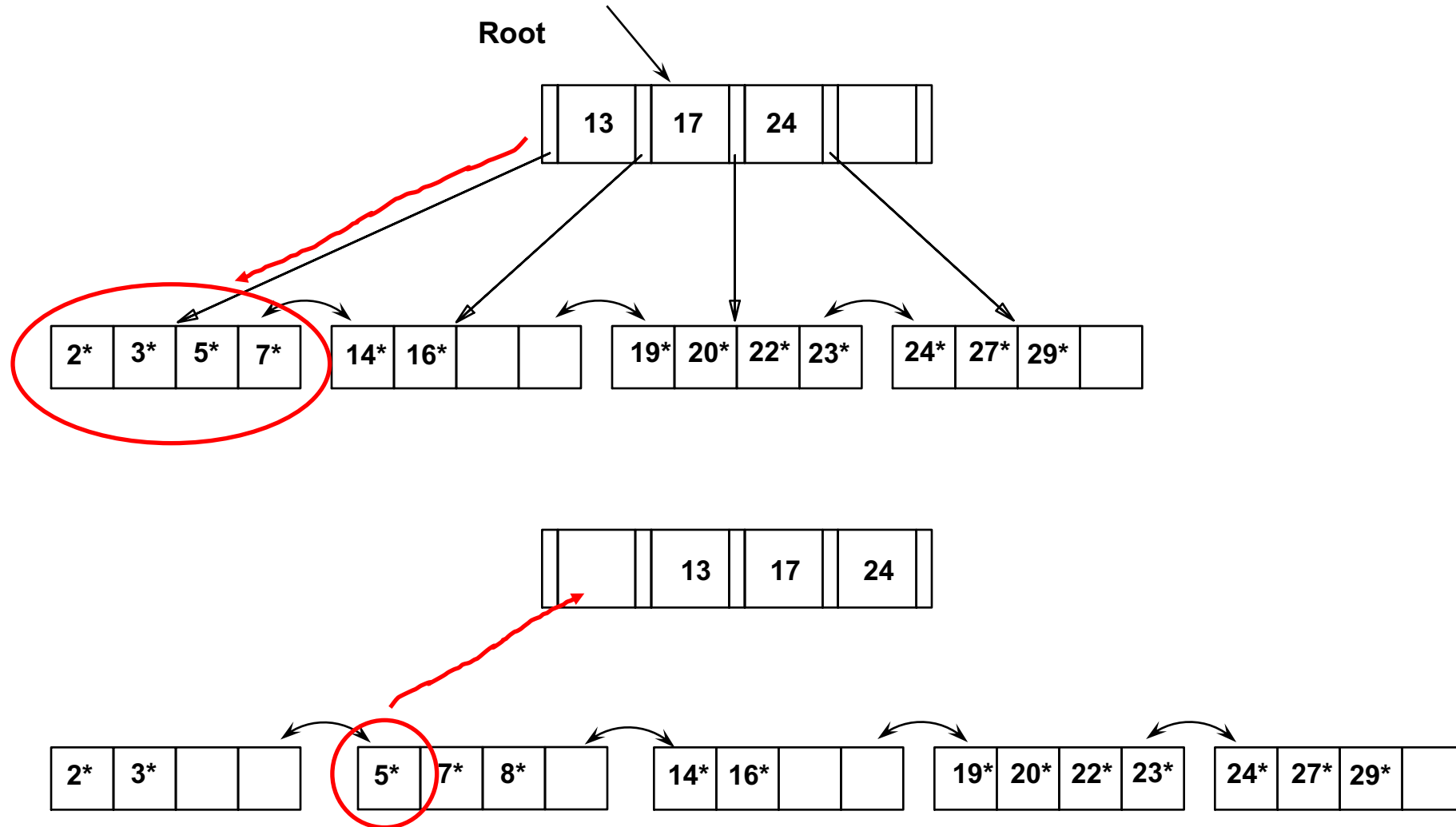
Example B+ Tree - Inserting 8*



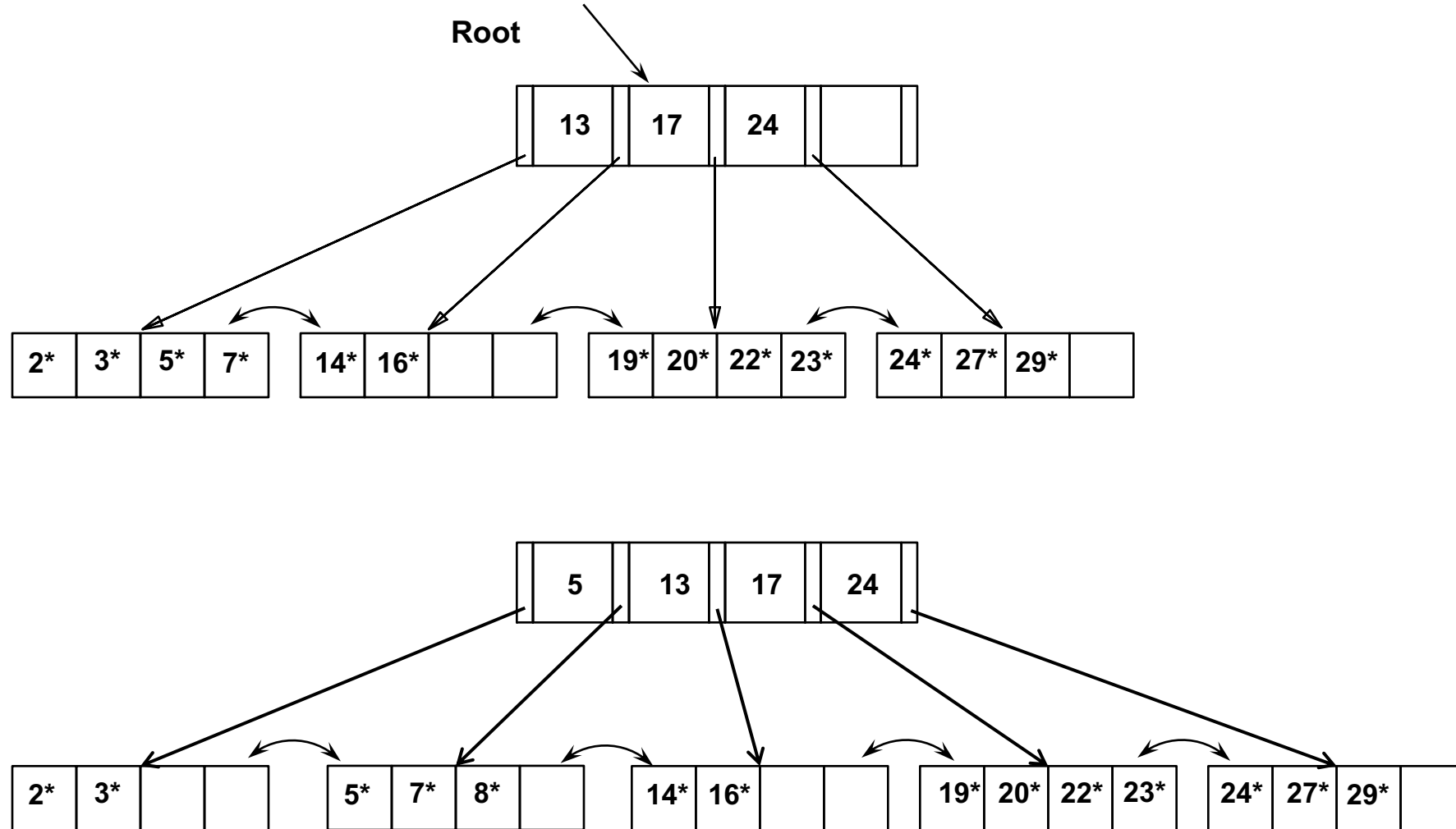
Example B+ Tree - Inserting 8*



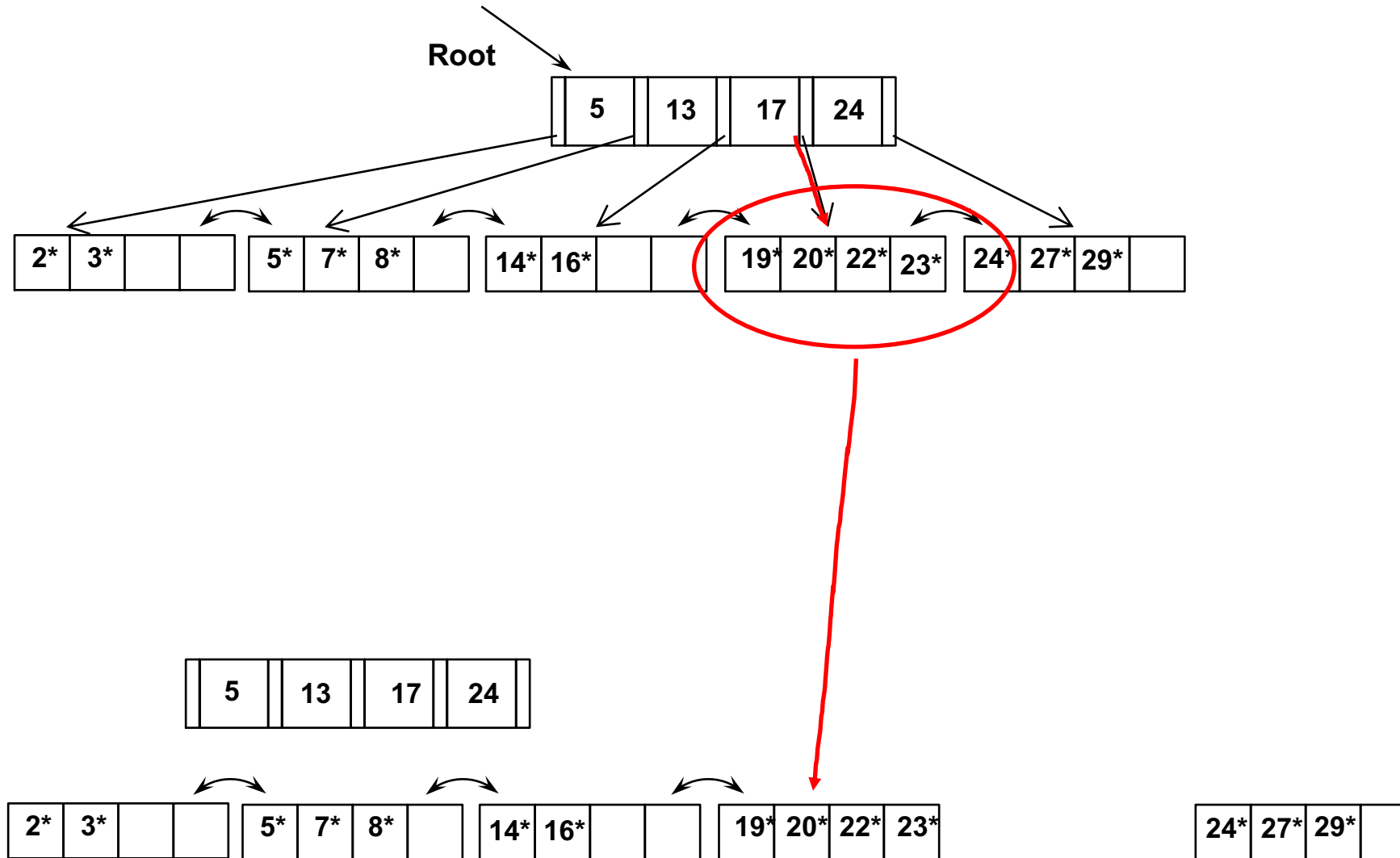
Example B+ Tree - Inserting 8*



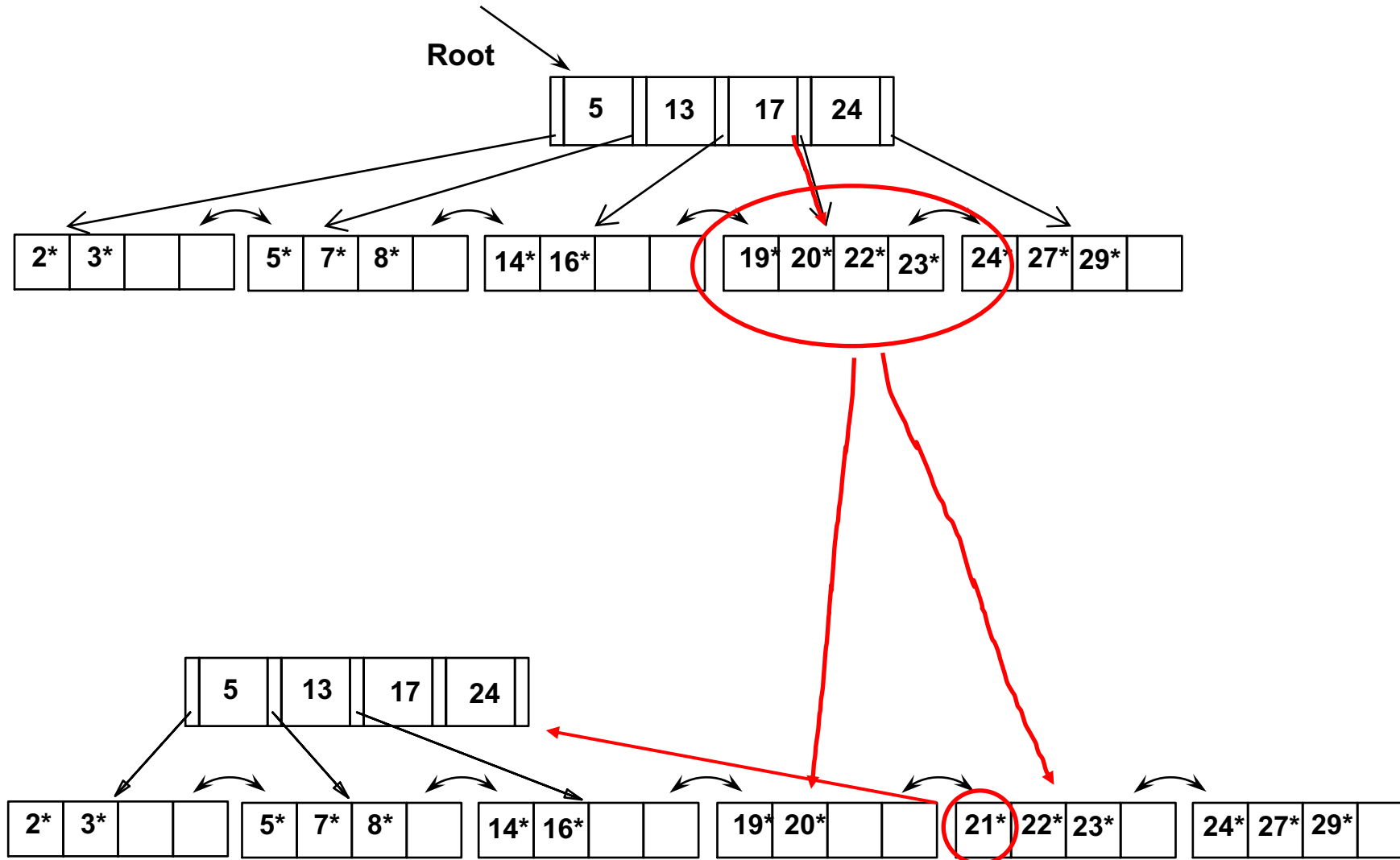
Example B+ Tree - Inserting 8*



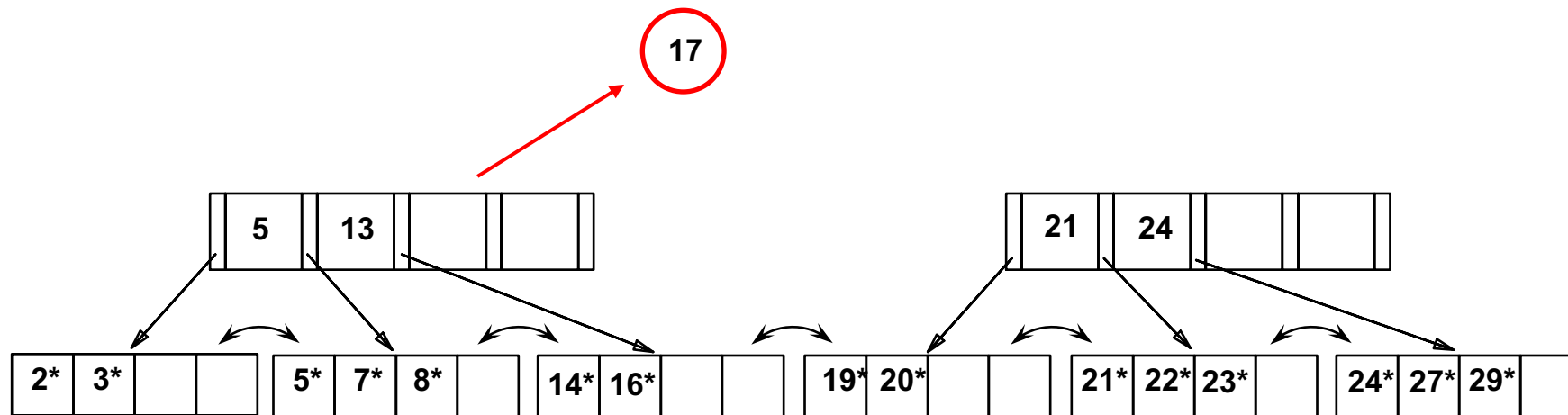
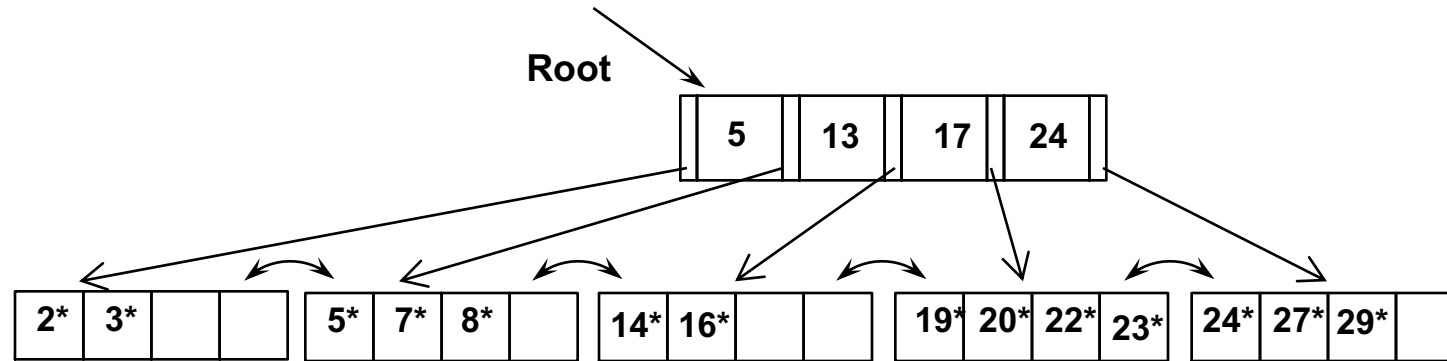
Example B+ Tree - Inserting 21*



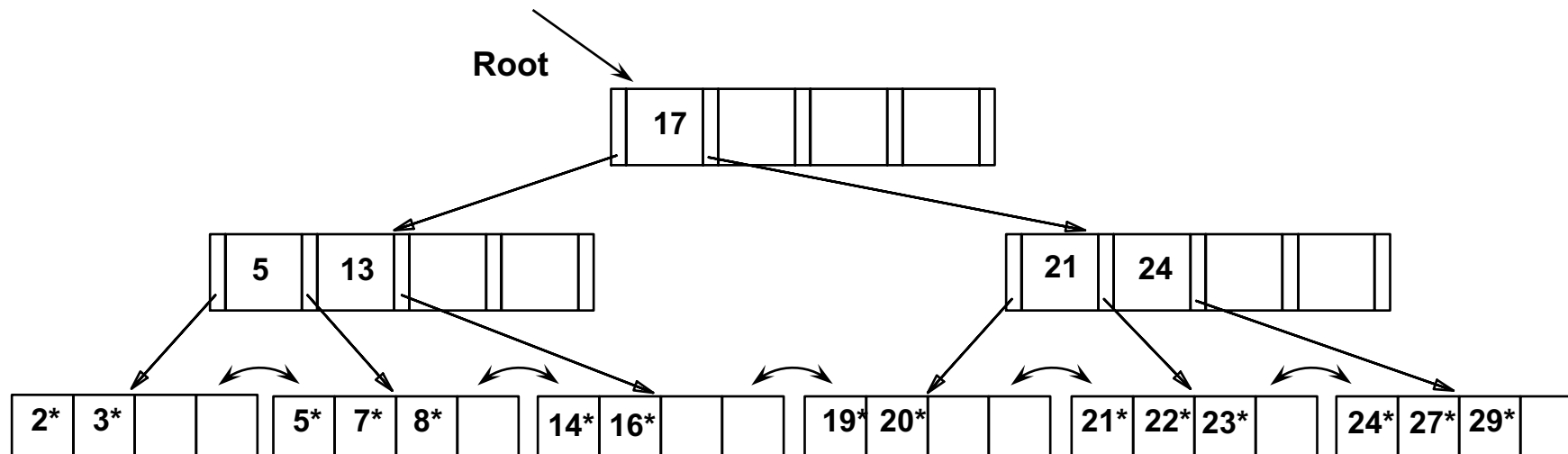
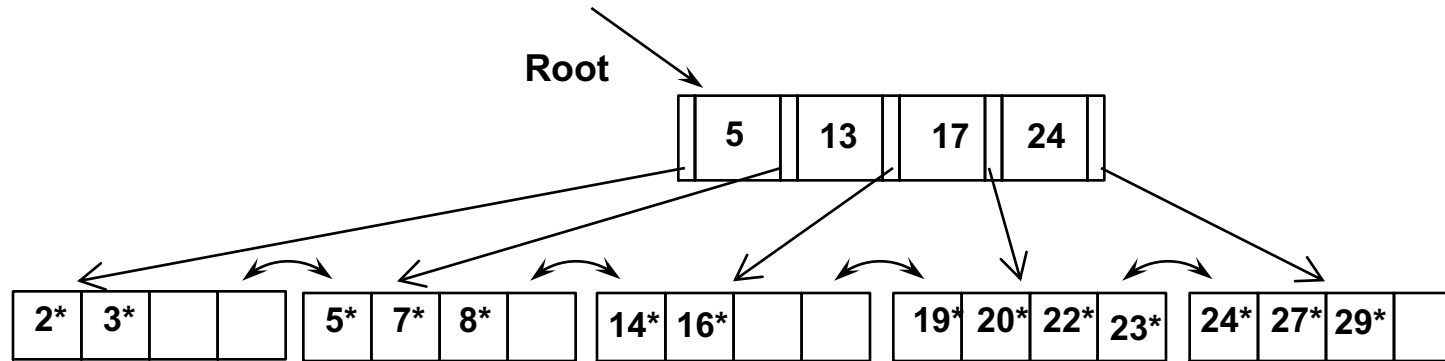
Example B+ Tree - Inserting 21*



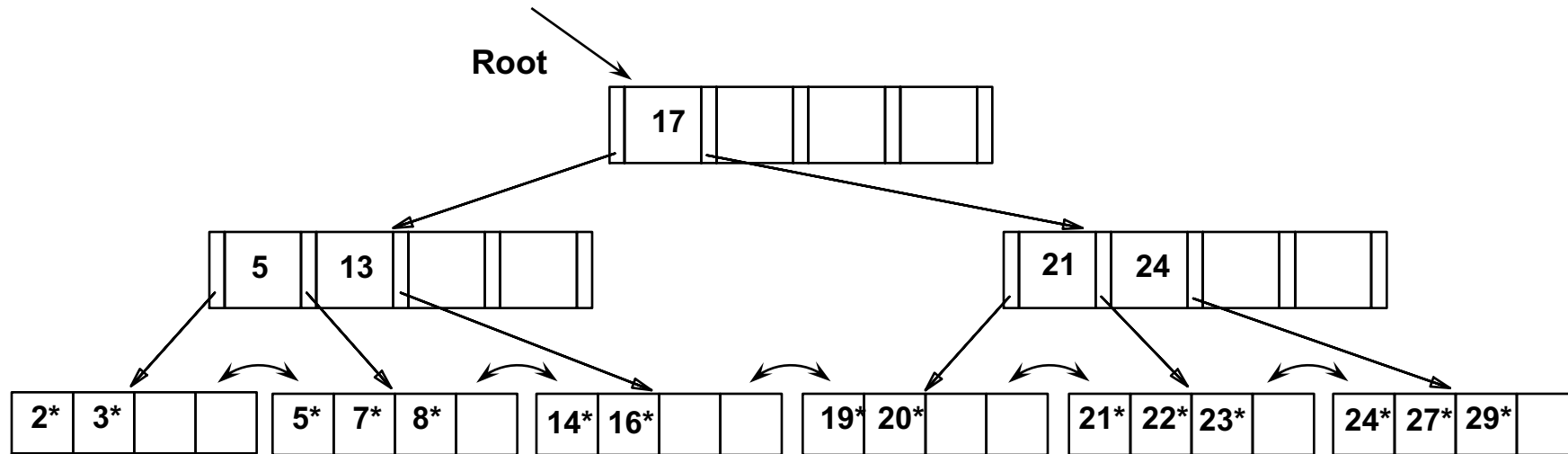
Example B+ Tree - Inserting 21*



Example B+ Tree - Inserting 21*



Example B+ Tree



Notice that root was split, leading to increase in height.

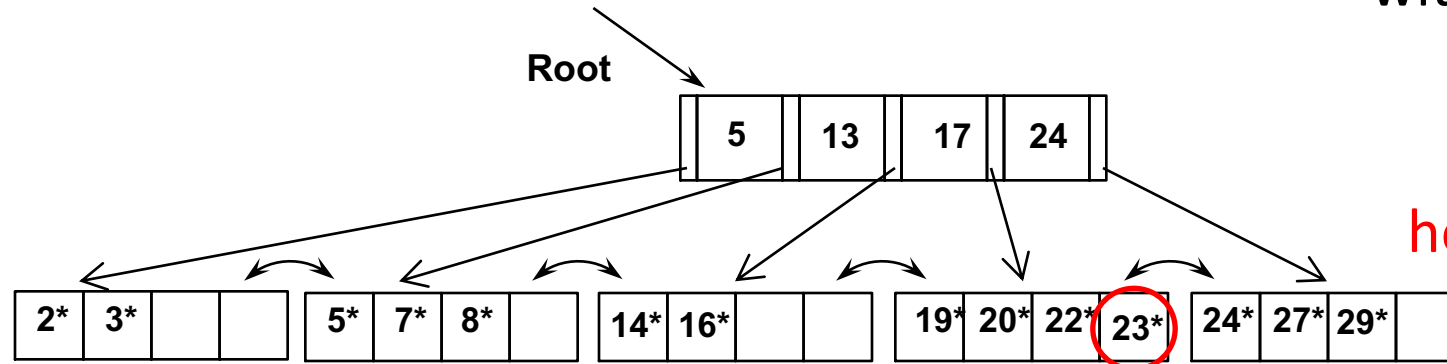
In this example, we can avoid split by re-distributing entries;
however, this is usually not done in practice.



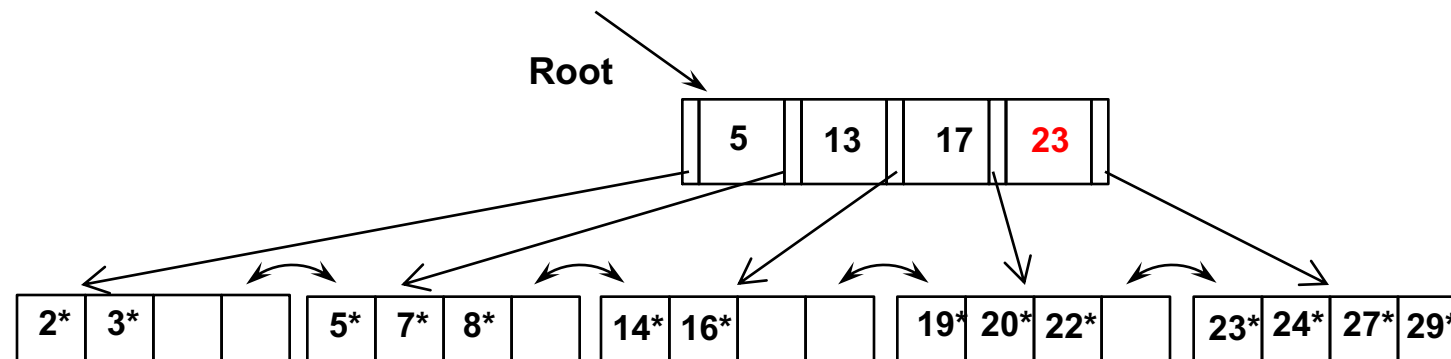
how to re-distribute entries?

Example B+ Tree - Inserting 21*

with redistribution

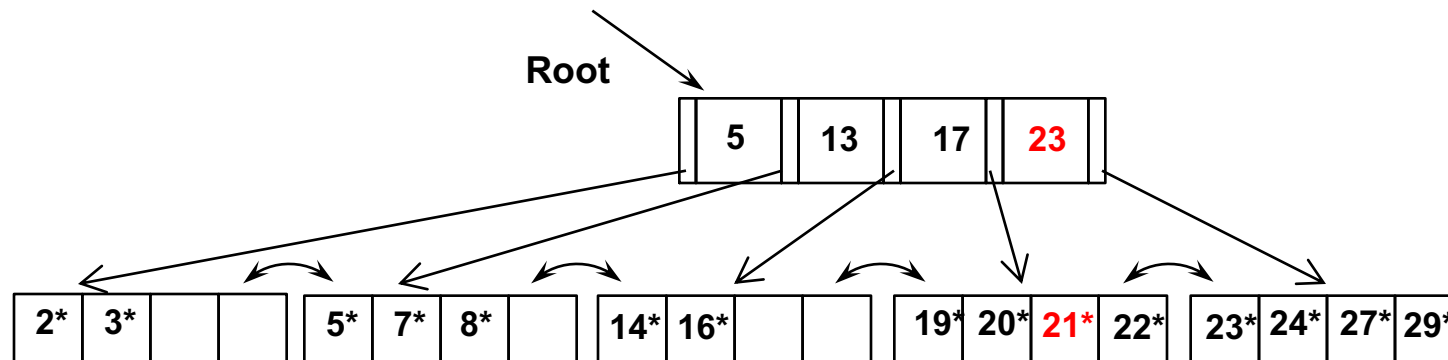
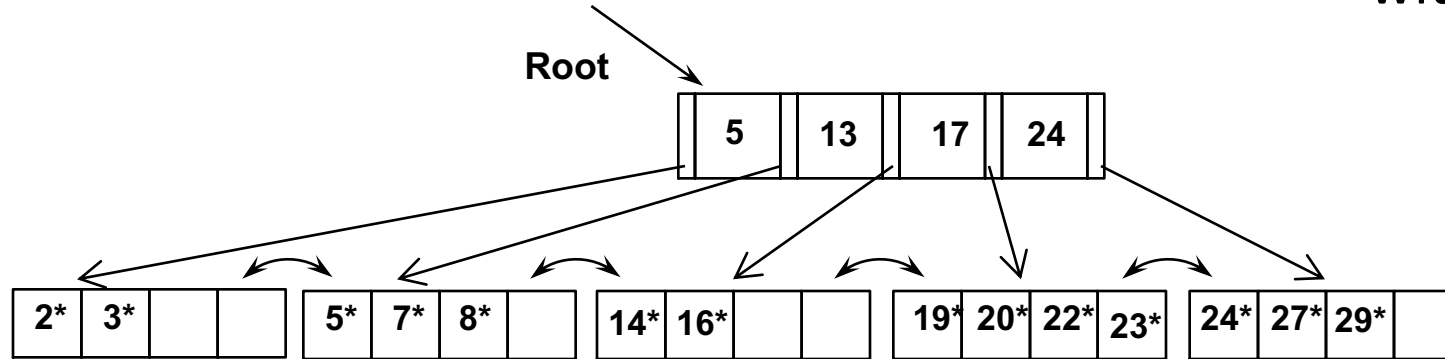


create space by moving one entry
& update parent node



Example B+ Tree - Inserting 21*

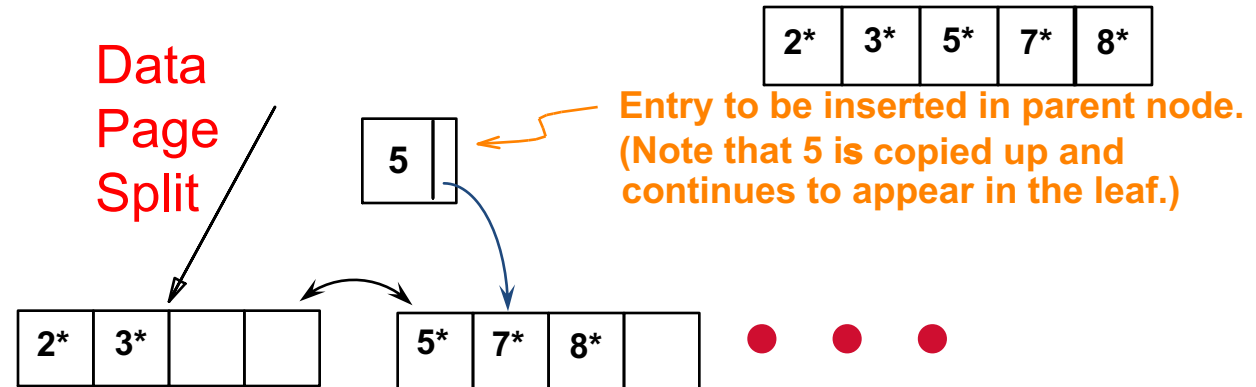
with redistribution



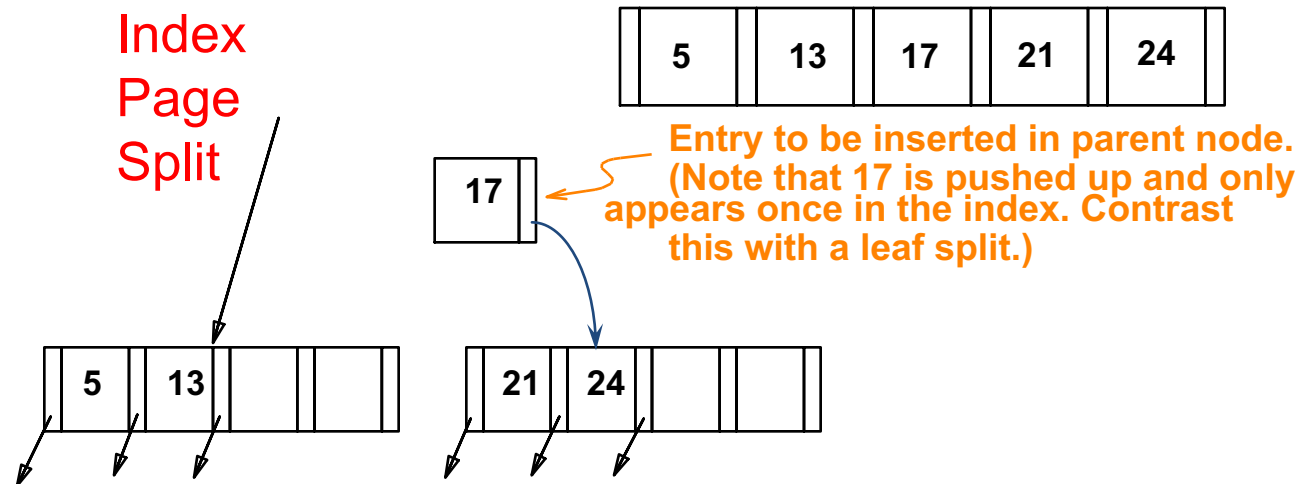
Example: Data vs. Index Page Split

minimum occupancy is guaranteed in both leaf and index page splits

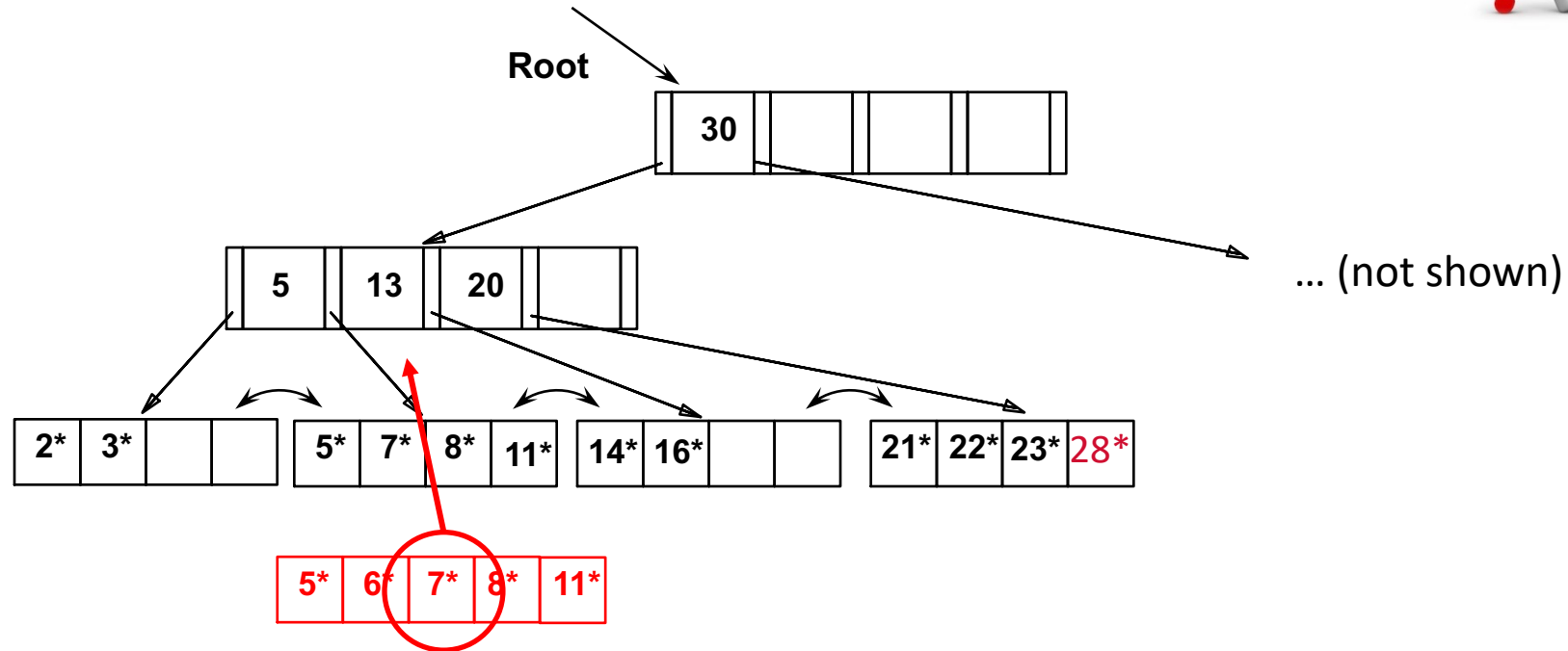
copy-up for data page splits



push-up for index page split



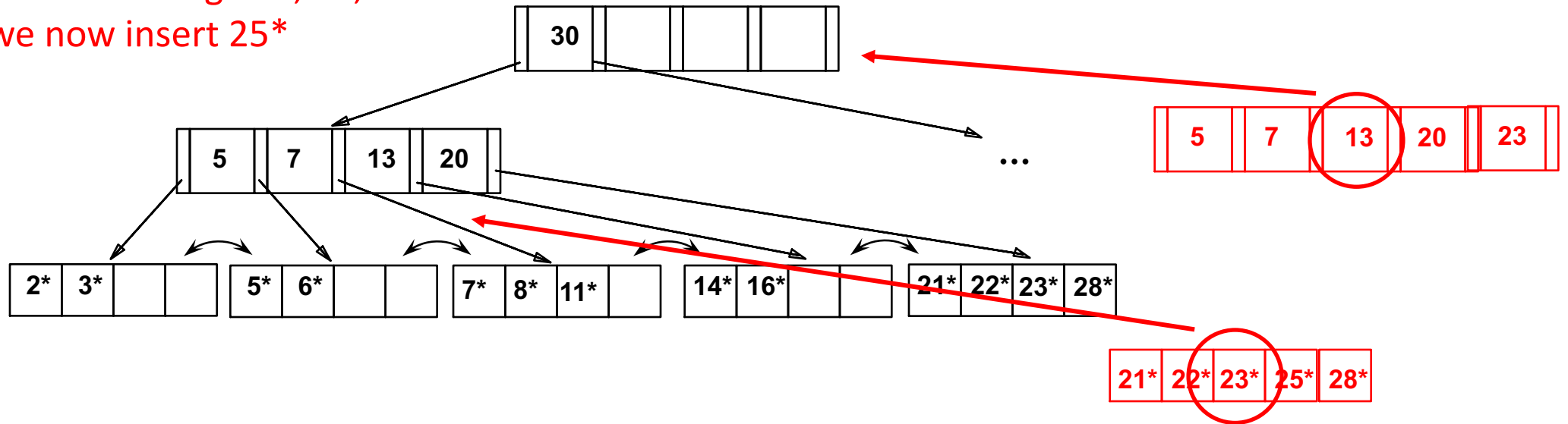
Now you try...



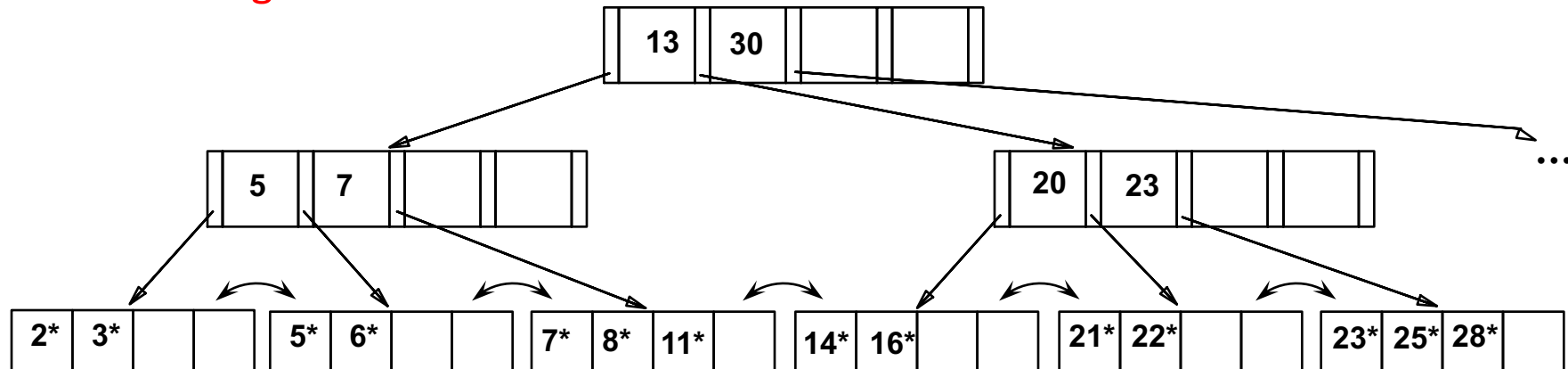
Insert the following data entries (in order): 28*, 6*, 25*

Answer...

After inserting 28*, 6*,
we now insert 25*



After inserting 25*



Tree-structured indexing

Intro & B⁺-Tree

Insert into a B⁺-Tree

Delete from a B⁺-Tree

Prefix Key Compression & Bulk Loading

Deleting a Data Entry from a B+ Tree

Start at root, find leaf L where entry belongs.

Remove the entry.

- If L is at least half-full, *done!*
- If L has only **$d-1$** entries,
 - Try to **re-distribute**, borrowing from sibling (*adjacent node with same parent as L*).
 - If re-distribution fails, **merge** L and sibling.

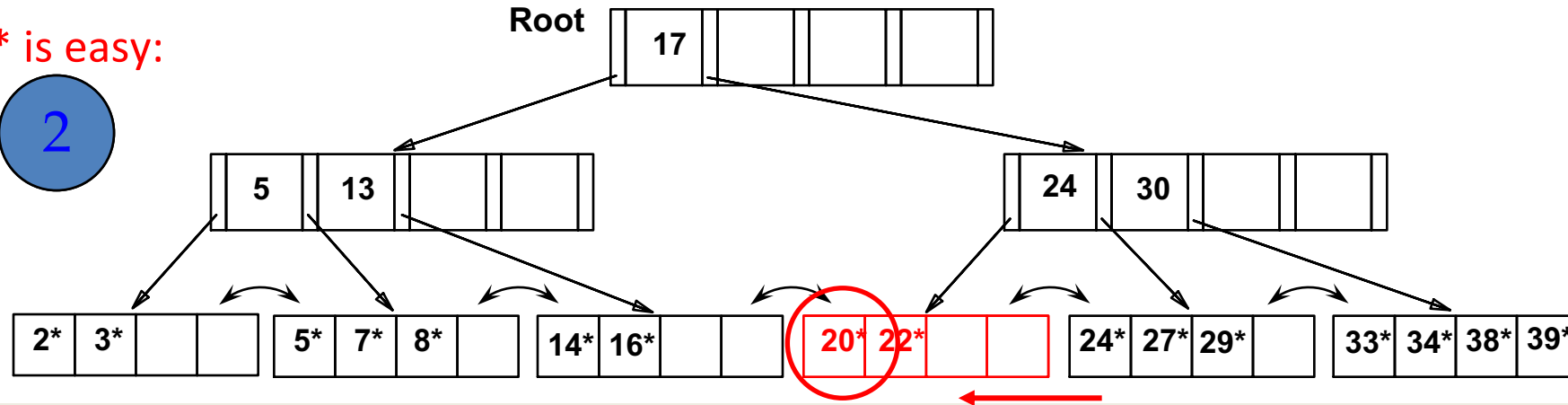
If merge occurred, must delete entry (pointing to L or sibling) from parent of L .

Merge could propagate to root, decreasing height.

Example: Delete 19* & 20*

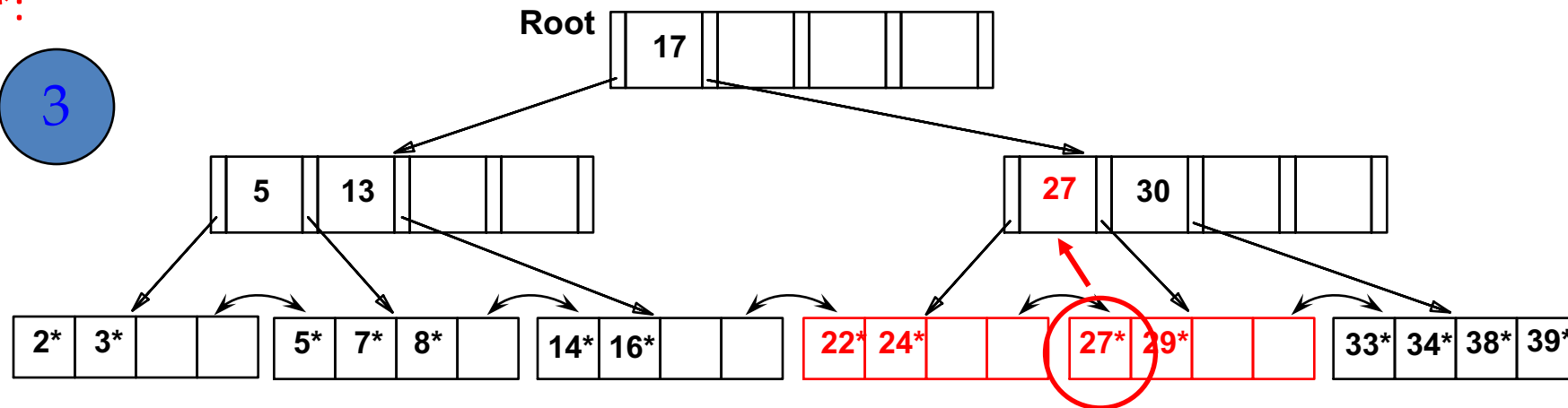
Deleting 19* is easy:

2



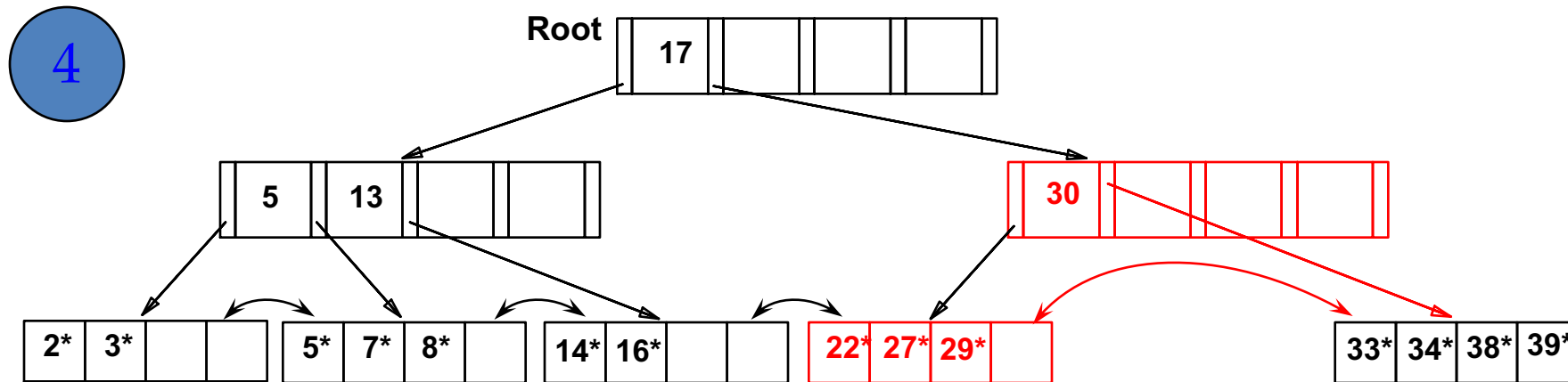
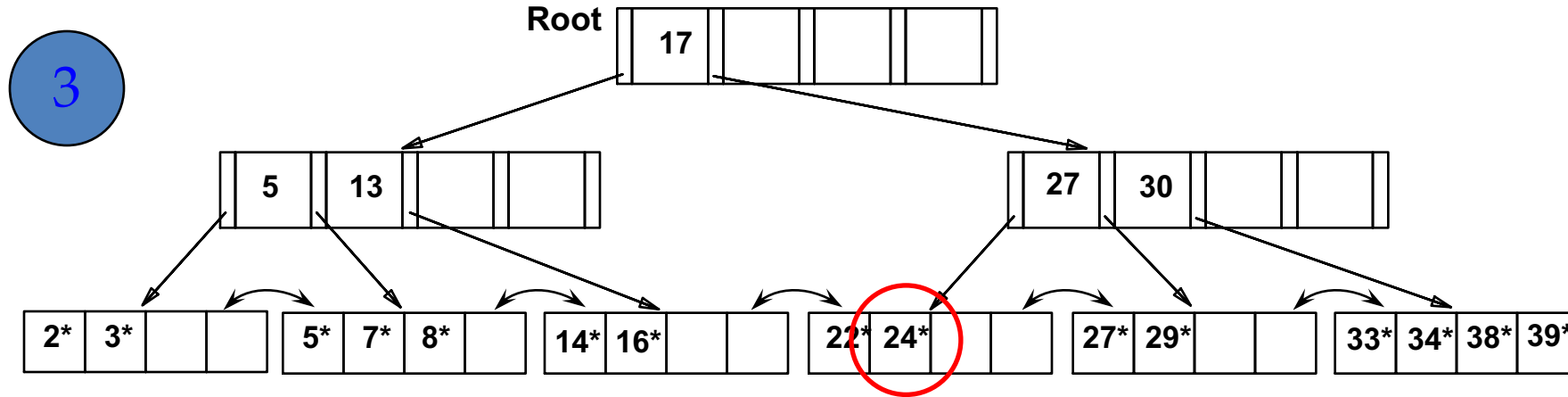
Deleting 20*:

3



Deleting 20* is done with **re-distribution**. Notice how middle key is *copied up*.

... and then deleting 24*

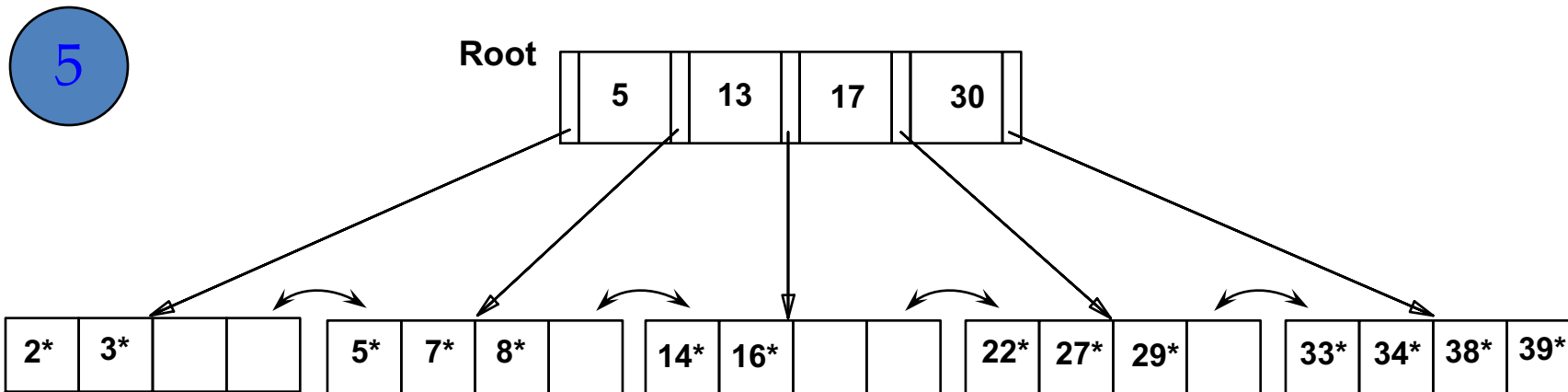
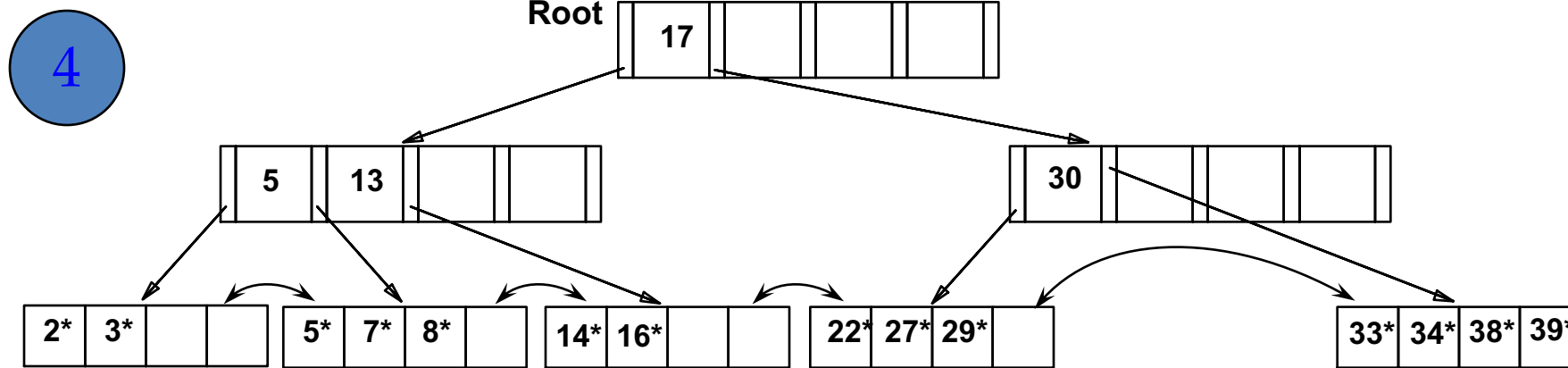


Must **merge** leaves

... but are we done??



... merge non-leaf nodes, shrink tree



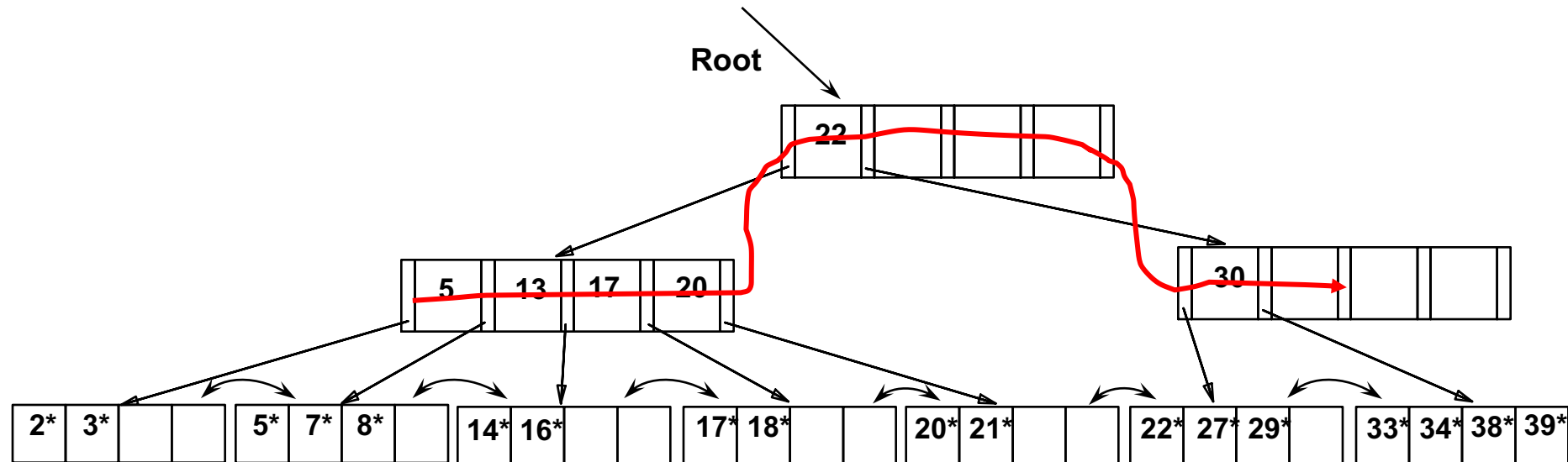
Example of non-leaf re-distribution

Tree is shown below *during deletion* of 24*.

What could be a possible initial tree?



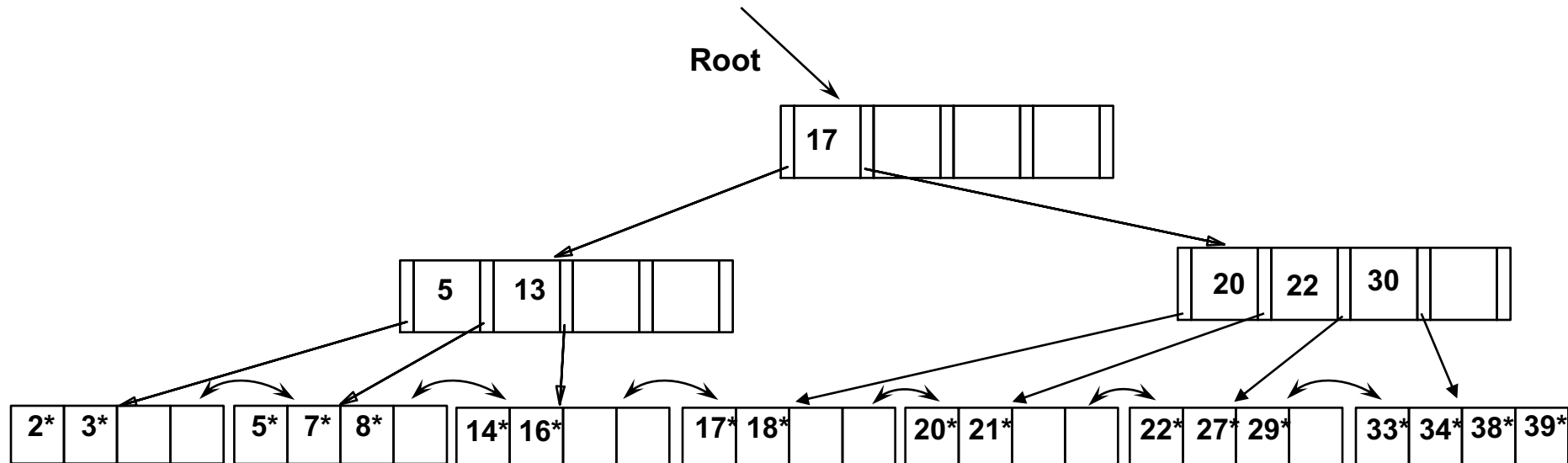
In contrast to previous example, can re-distribute entry from left child of root to right child.



After Re-distribution

Intuitively, entries are **re-distributed by “pushing through”** the splitting entry in the parent node.

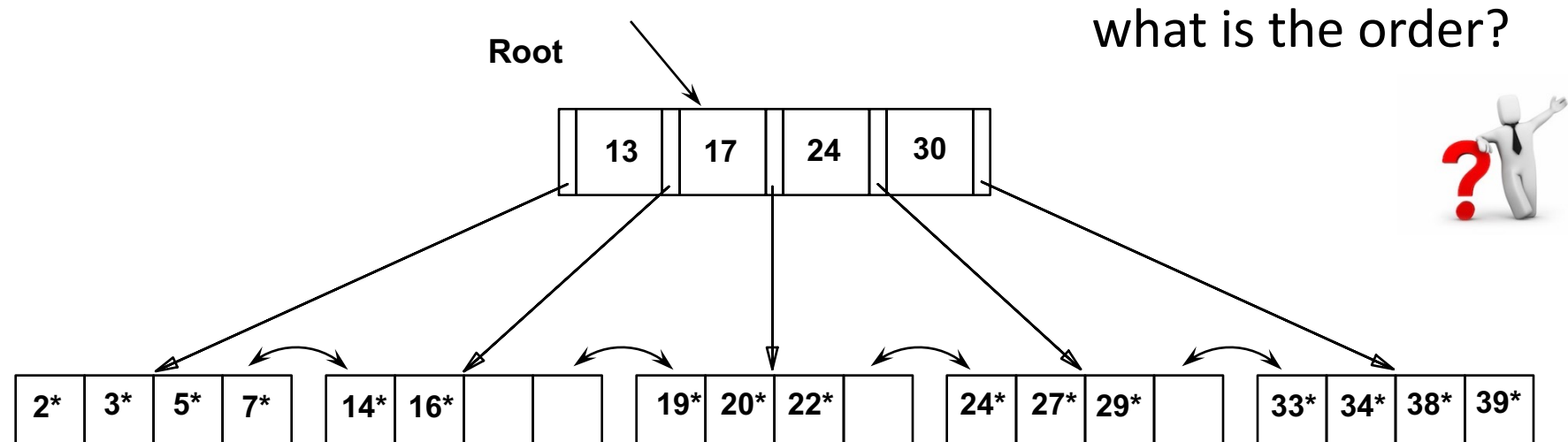
it suffices to re-distribute index entry with key 20;
we have re-distributed 17 as well for illustration



Reminders

begin at root, compare keys to reach the leaf

“order” d means d to 2^*d elements



Tree-structured indexing

Intro & B⁺-Tree

Insert into a B⁺-Tree

Delete from a B⁺-Tree

Prefix Key Compression & Bulk Loading

Prefix Key Compression

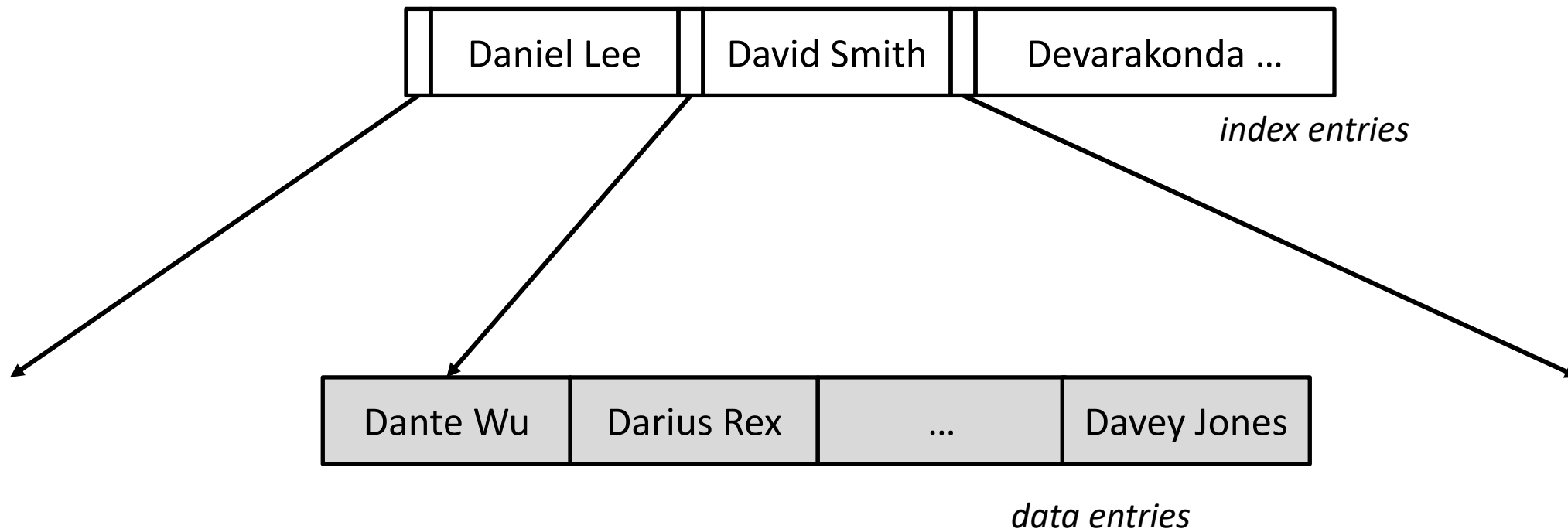
we want to increase fan-out

why?



key values in index entries (internal nodes) are used to “direct traffic”

how to compress?



Prefix Key Compression

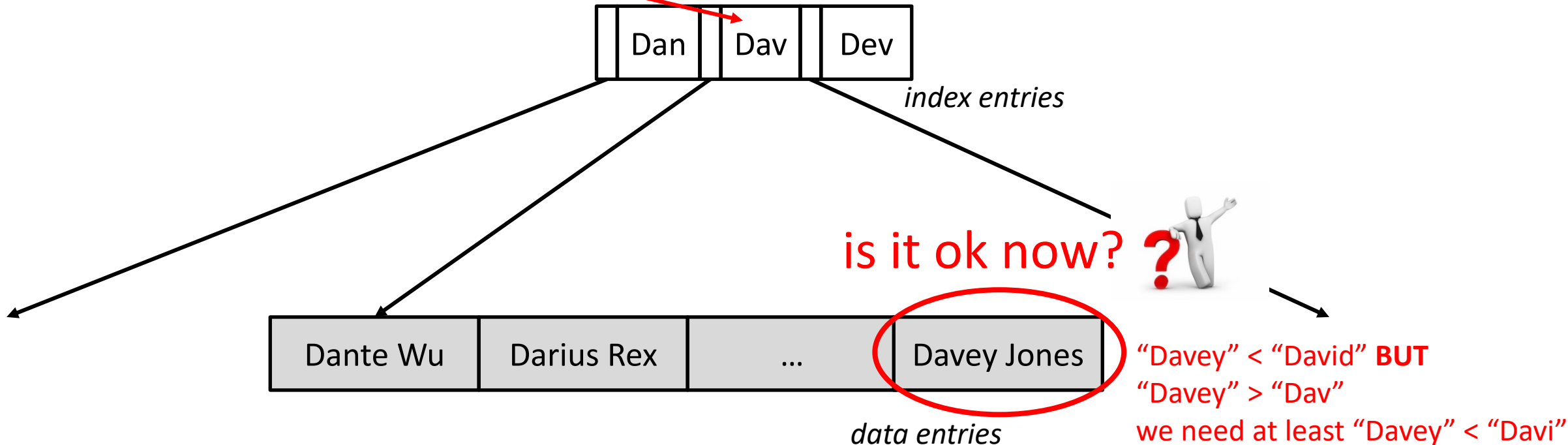
we want to increase fan-out

why? 

key values in index entries (internal nodes) are used to “direct traffic”

how to compress? 

remember: David Smith



Prefix Key Compression

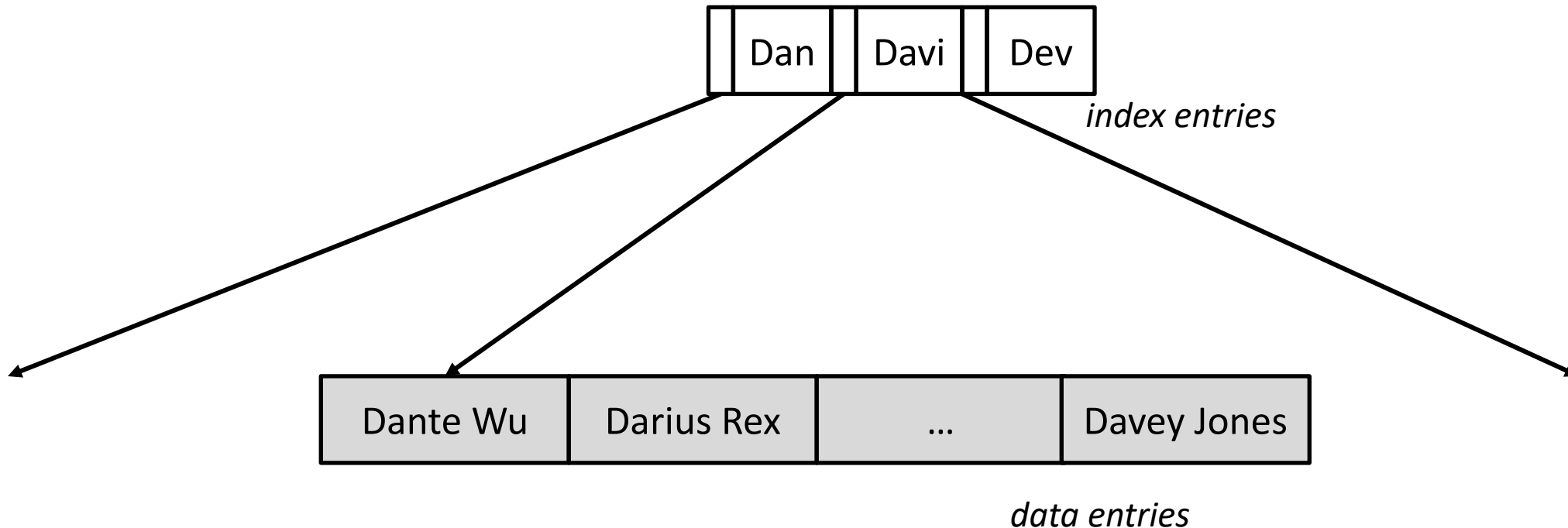
we want to increase fan-out

why?



key values in index entries (internal nodes) are used to “direct traffic”

how to compress?



Prefix Key Compression

we want to increase fan-out

keys in index entries (internal nodes) are used to “direct traffic”

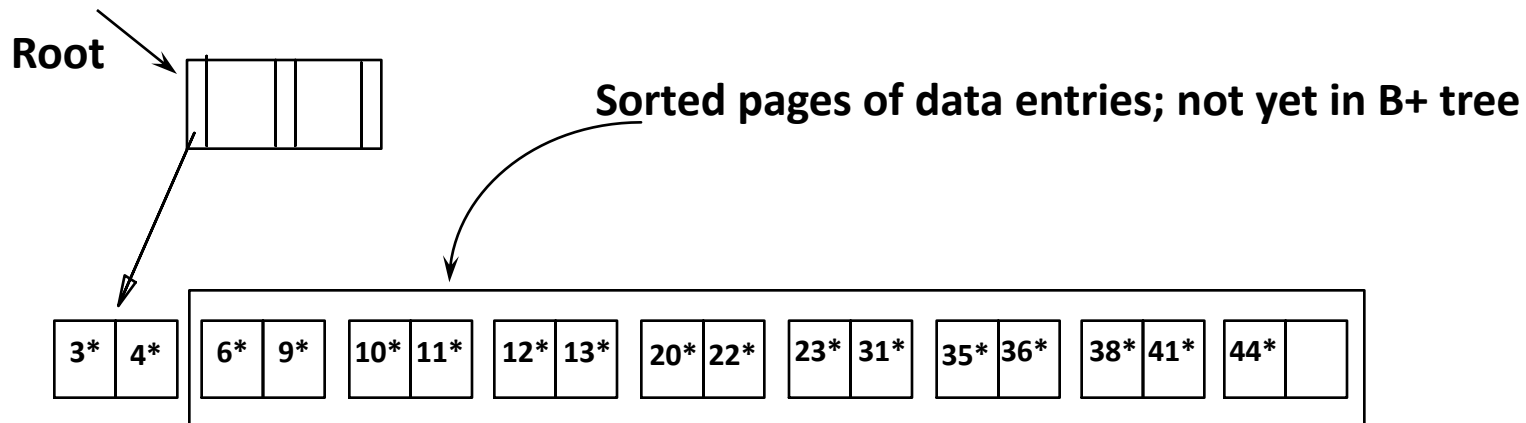
insert/delete must be suitably modified

Bulk Loading of a B+ Tree

If we have a large collection of records, and we want to create a B+ tree on some field, doing so by repeatedly inserting records is very slow.

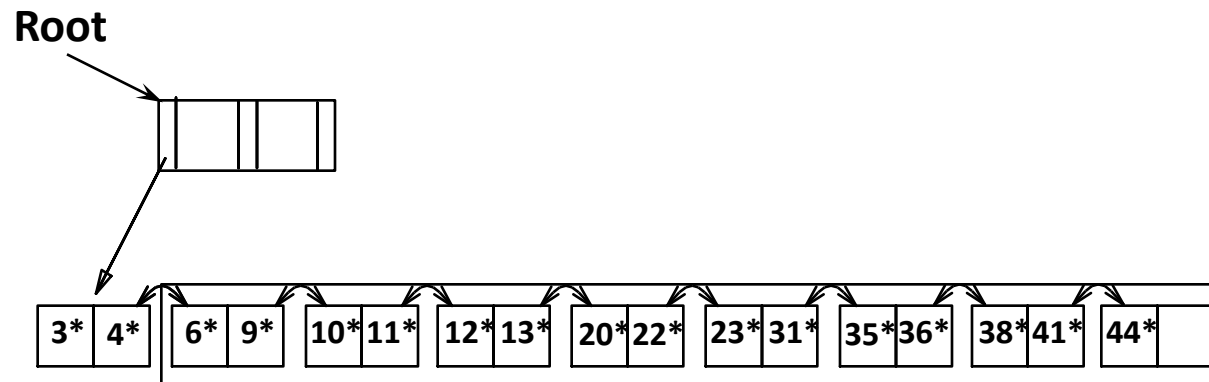
Bulk Loading can be done much more efficiently.

Initialization: Sort all data entries, insert pointer to first (leaf) page in a new (root) page.



Bulk Loading (Contd.)

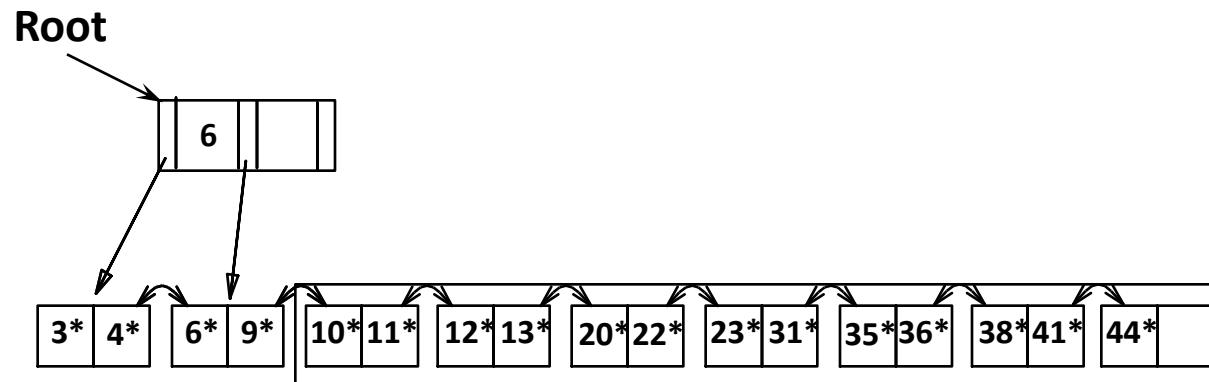
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

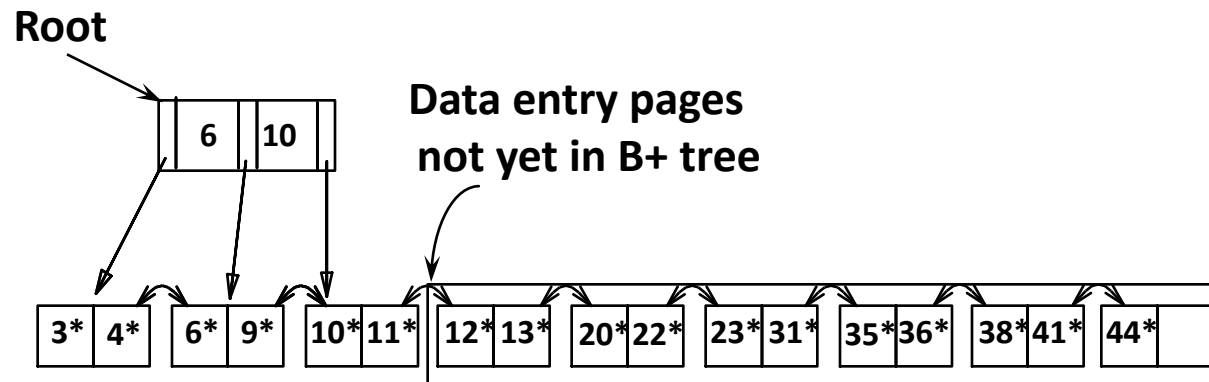
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

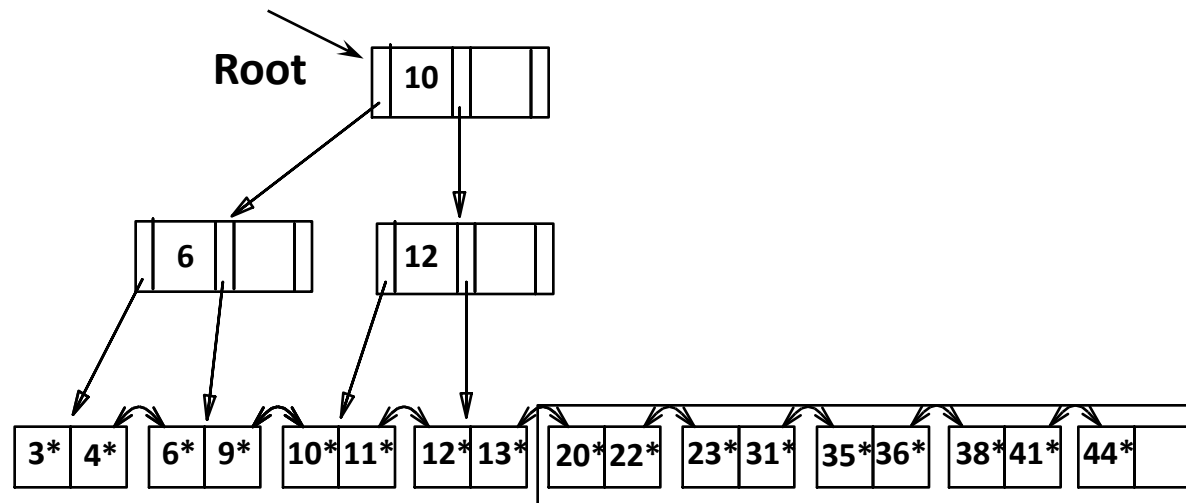
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

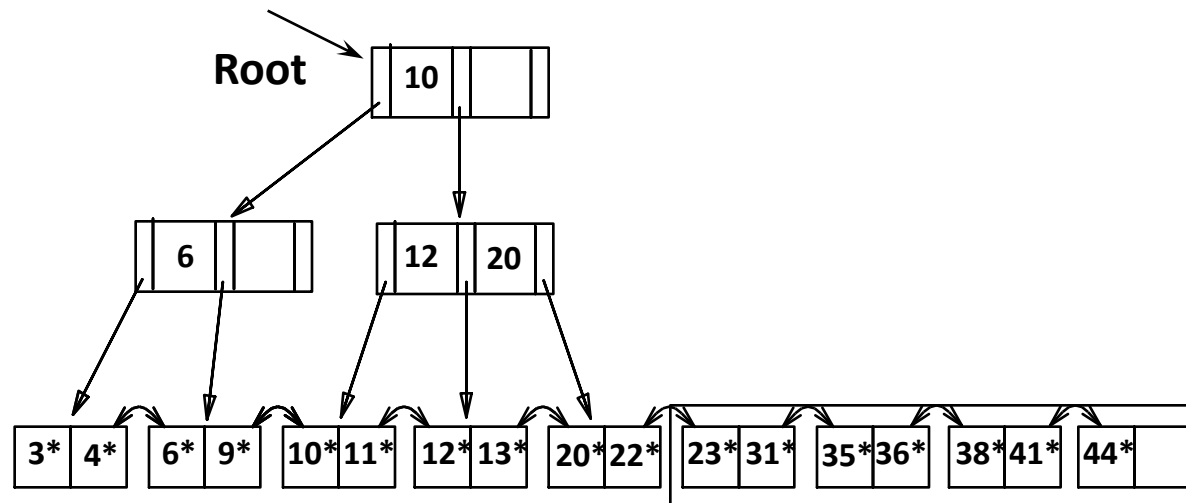
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

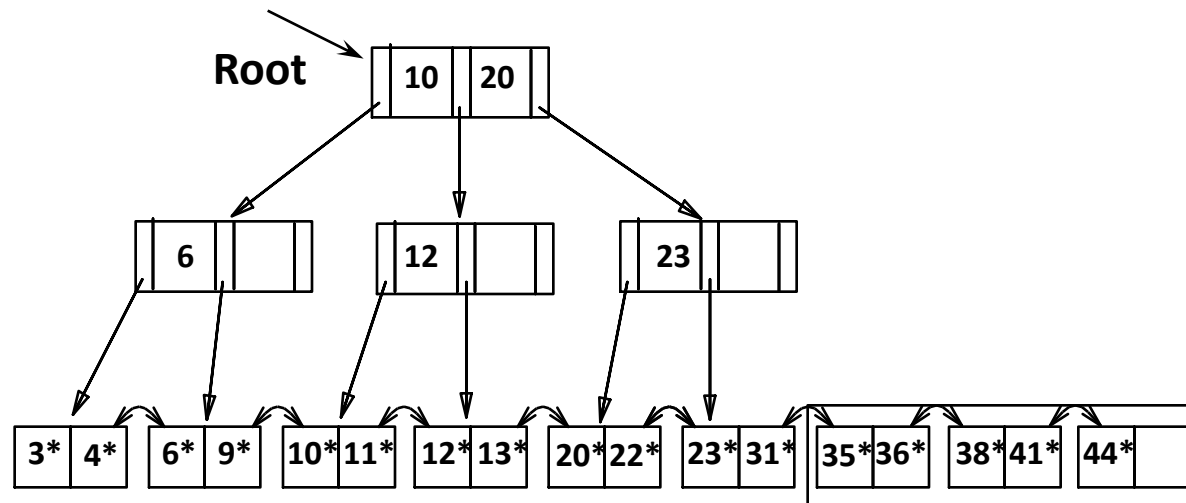
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

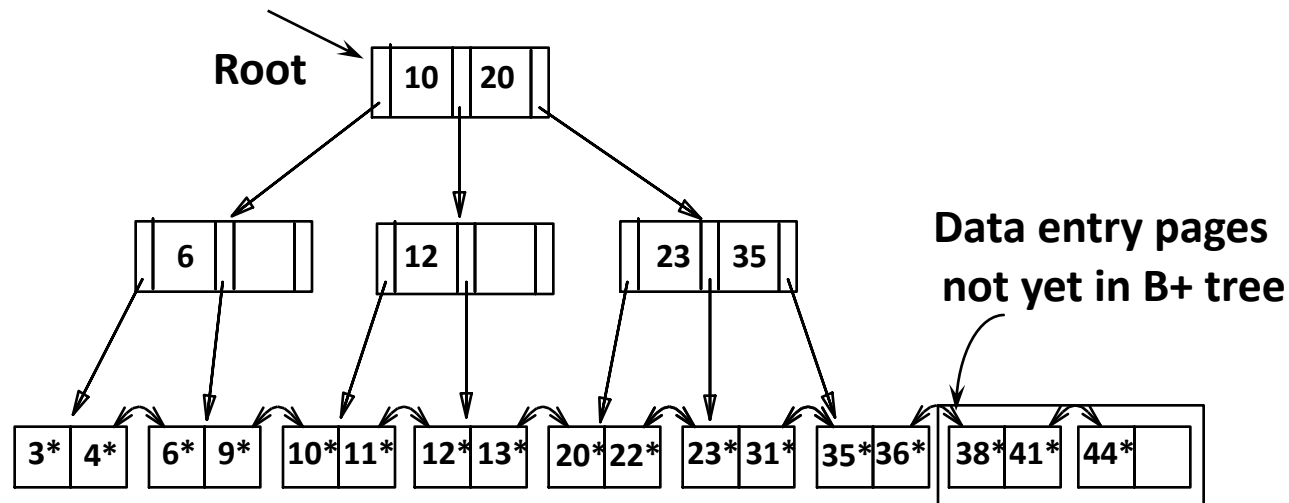
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

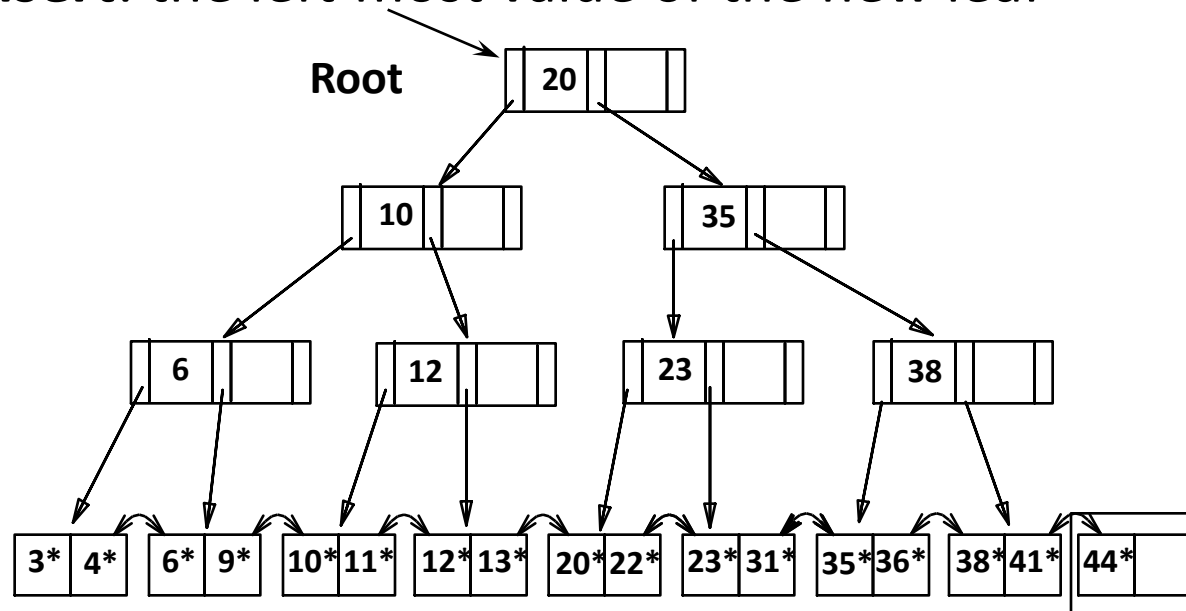
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

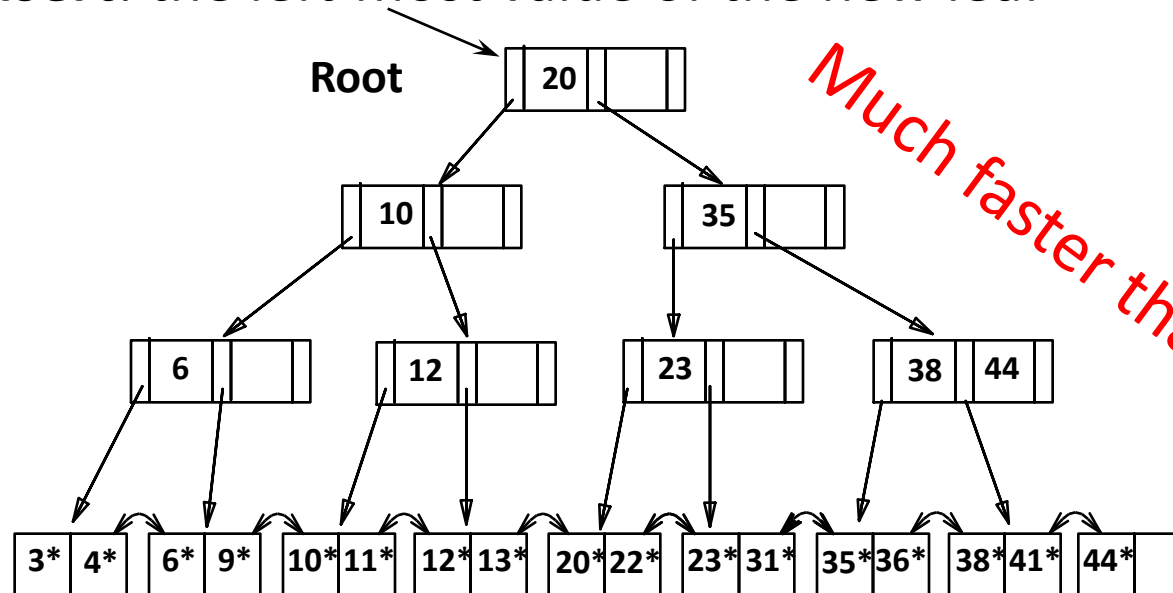
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Contd.)

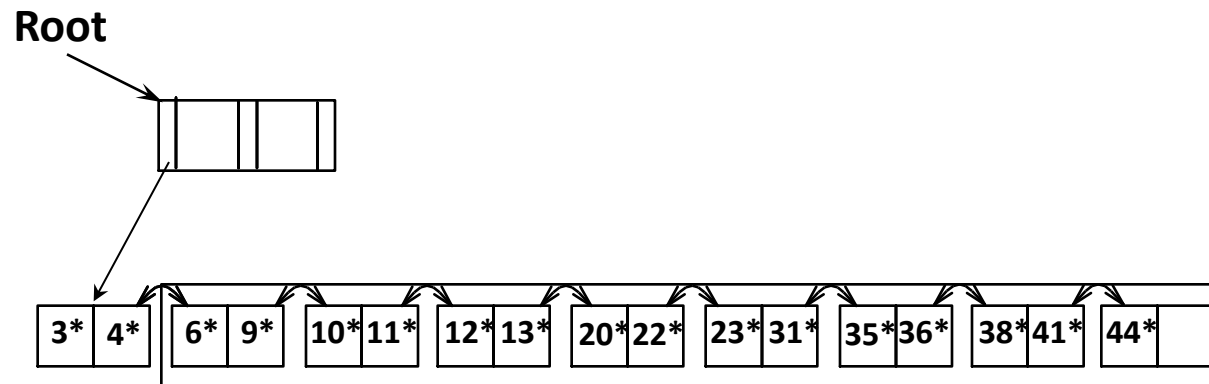
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, splits node
 (if needed split may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

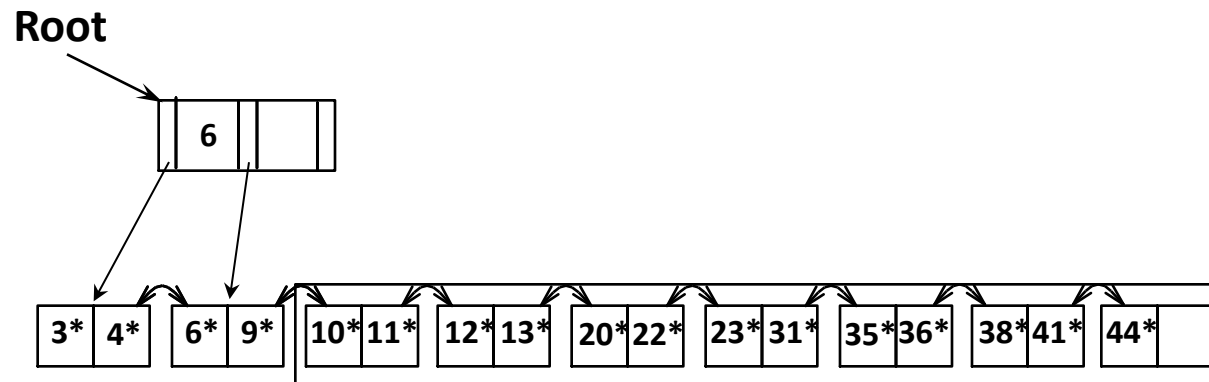
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value
 (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

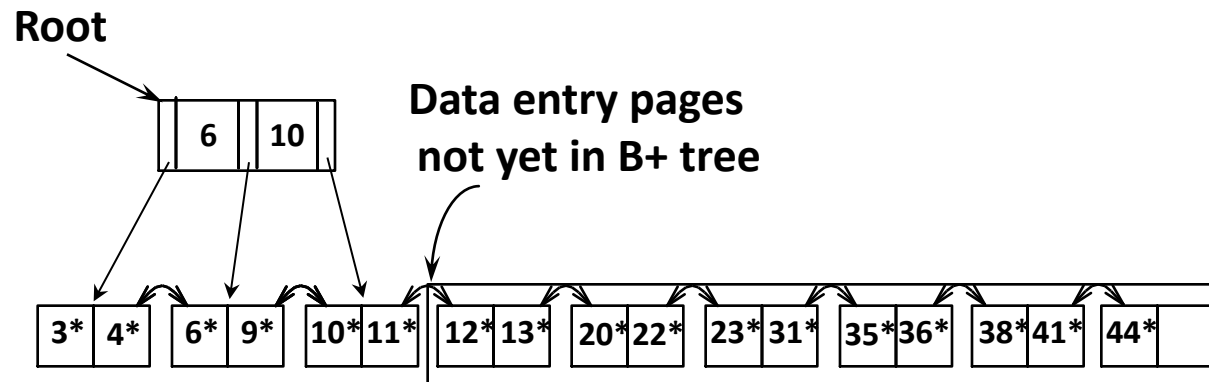
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value
 (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf

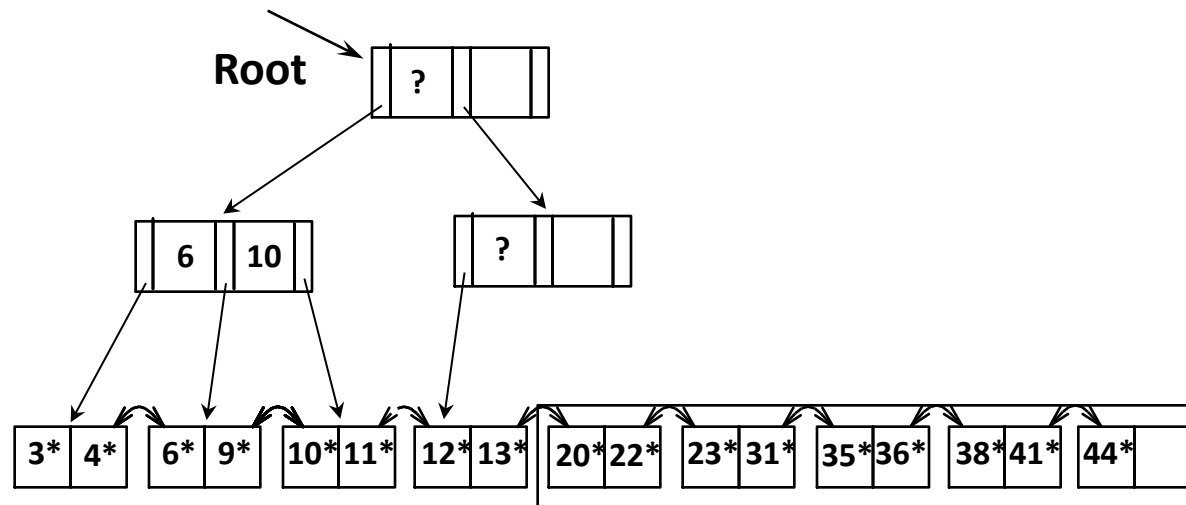


what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

where to insert: into right-most index page just above leaf level

what to insert: the left-most value of the new leaf

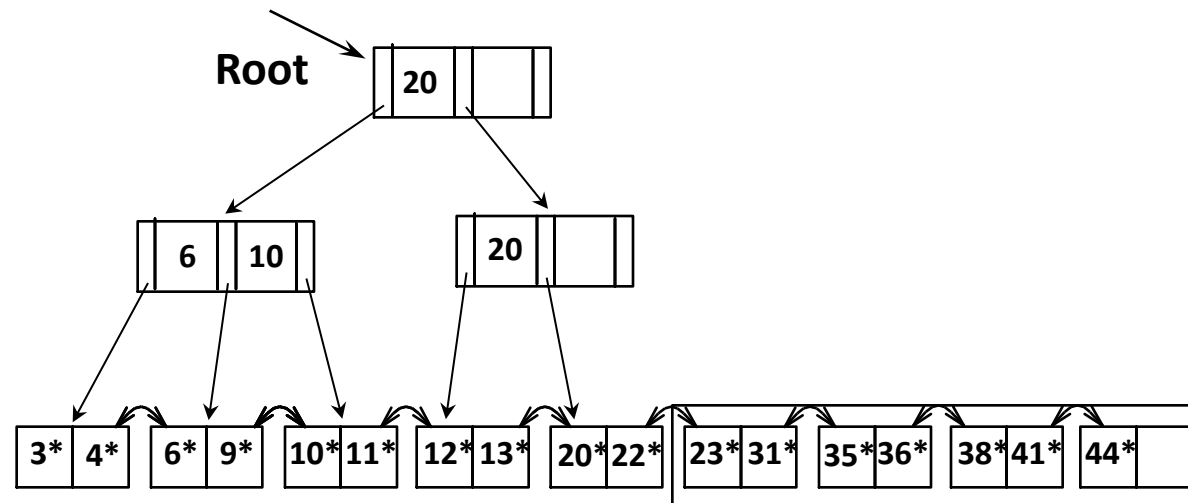


what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

where to insert: into right-most index page just above leaf level

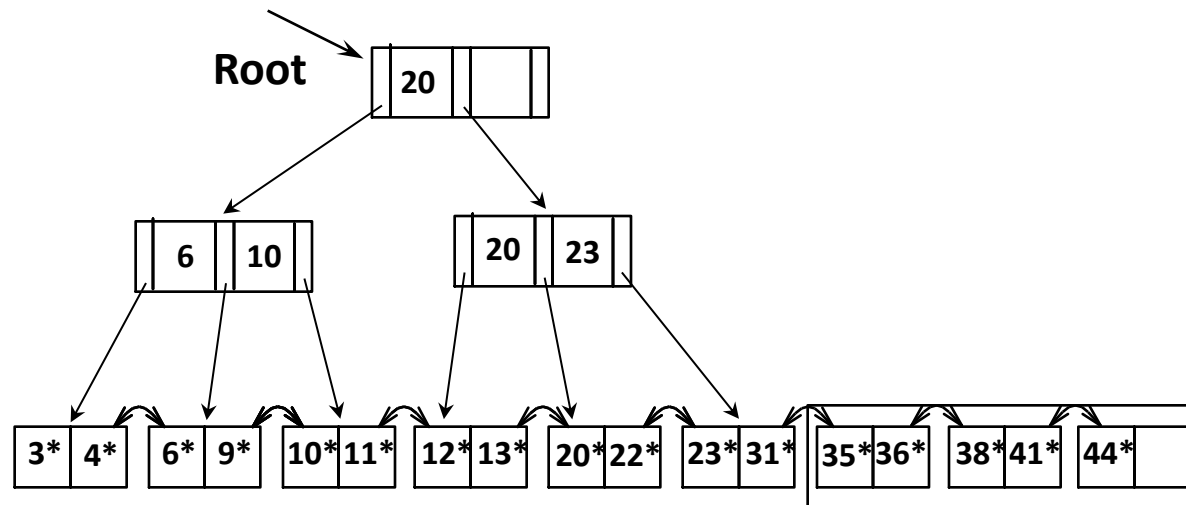
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

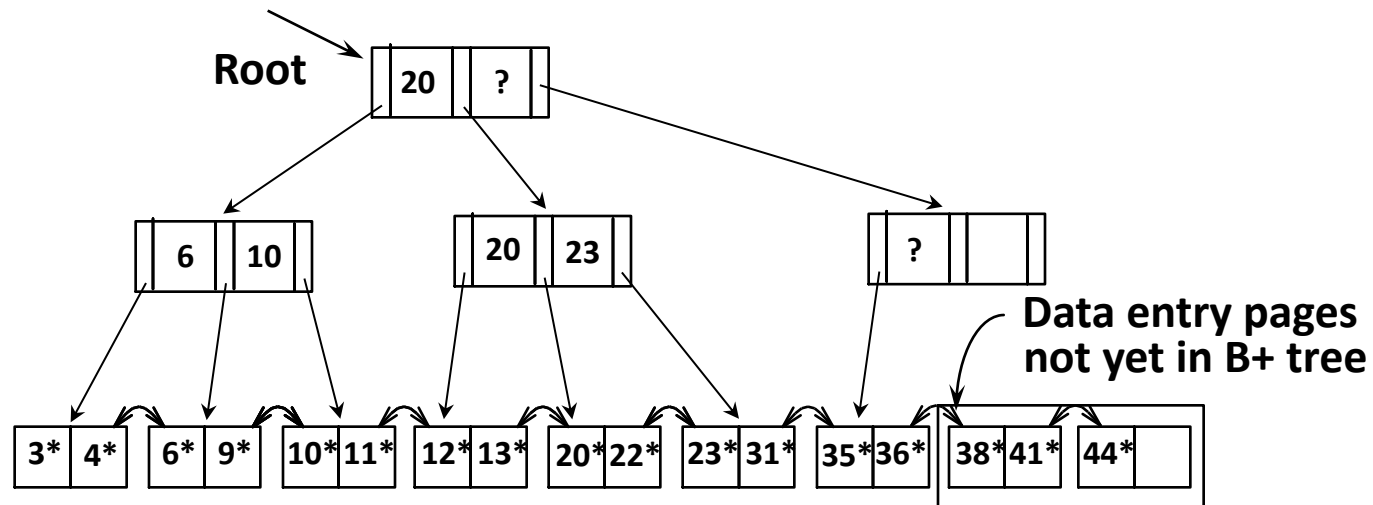
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value
 (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

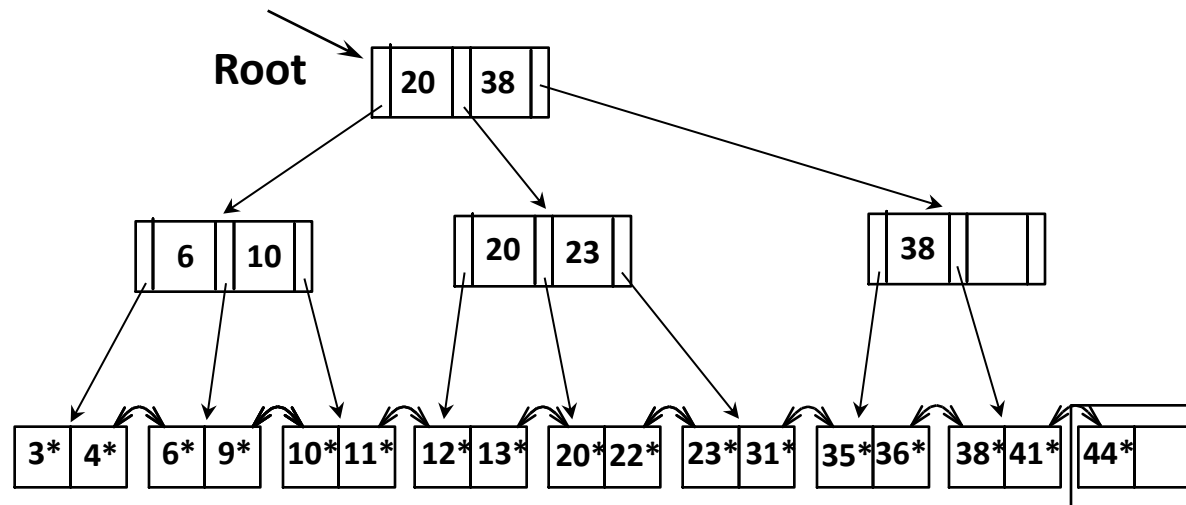
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf

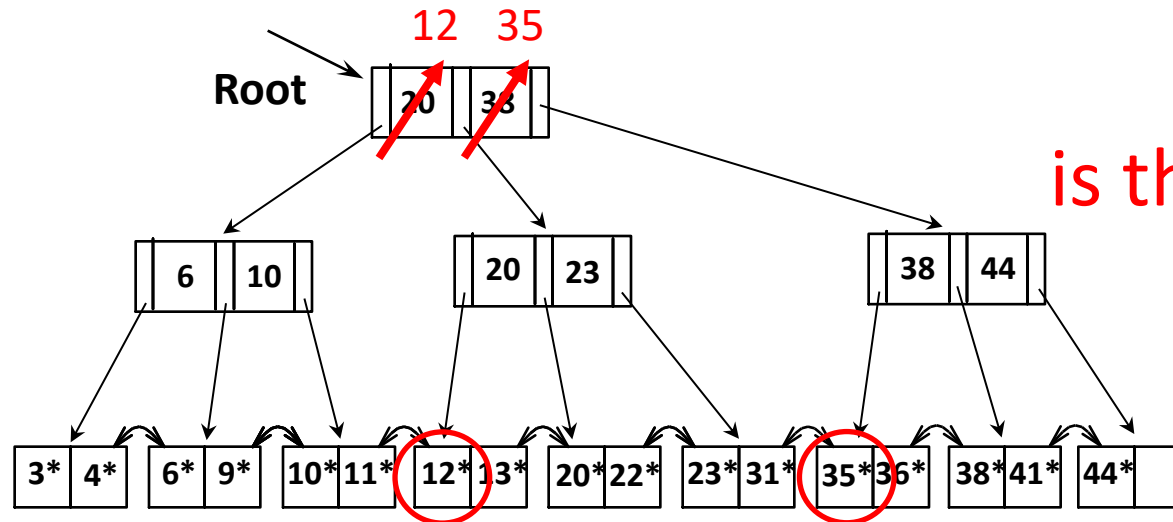


what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio)

where to insert: into right-most index page just above leaf level

what to insert: the left-most value of the new leaf



is this correct? ?

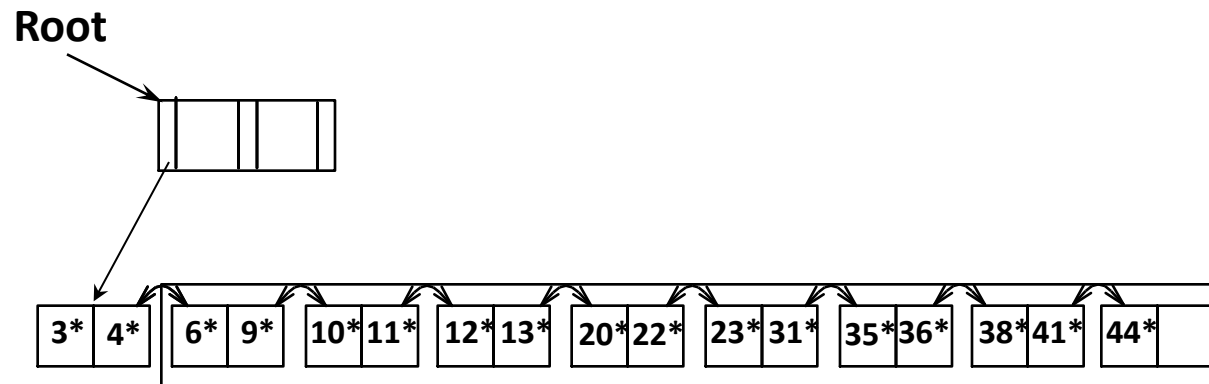


need to propagate the left most key

what to do when full? when this fills up, create new empty node and propagate a pointer with an empty value (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

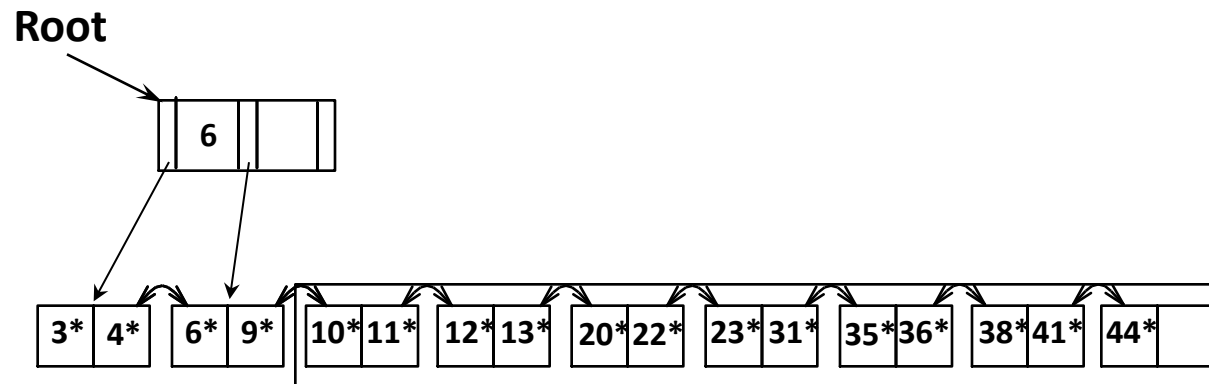
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

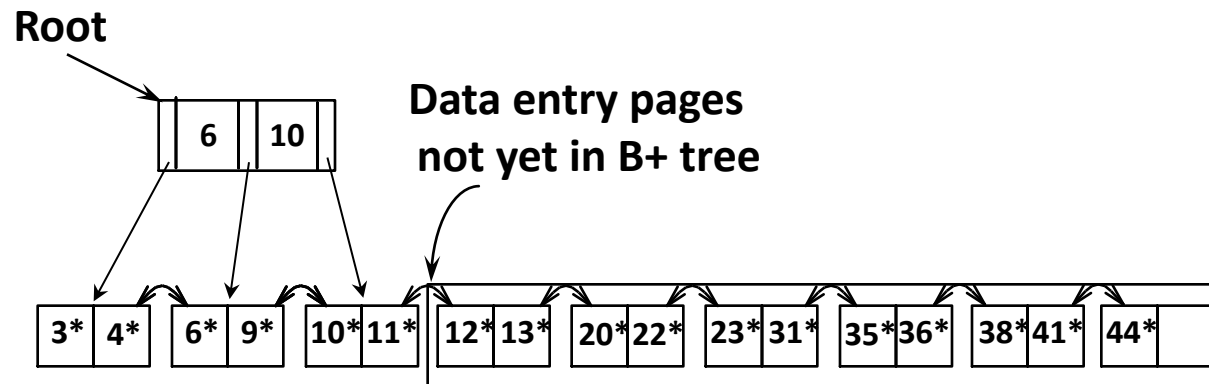
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

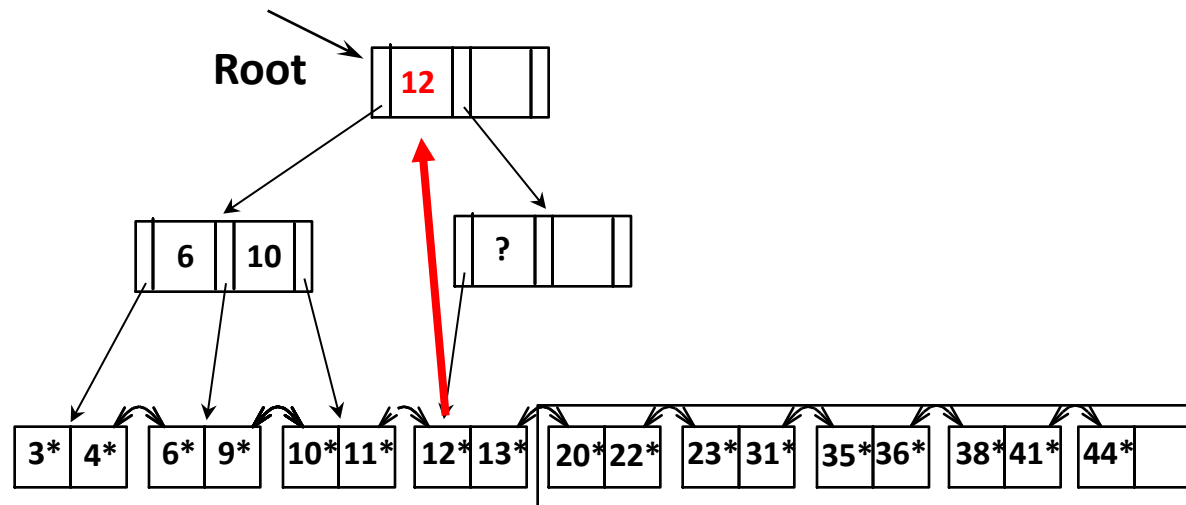
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

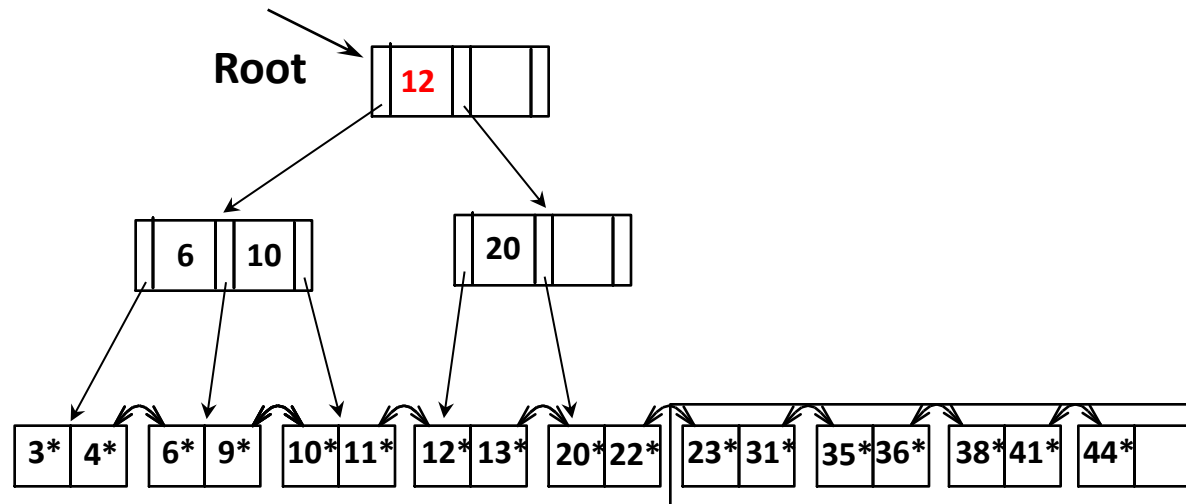
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

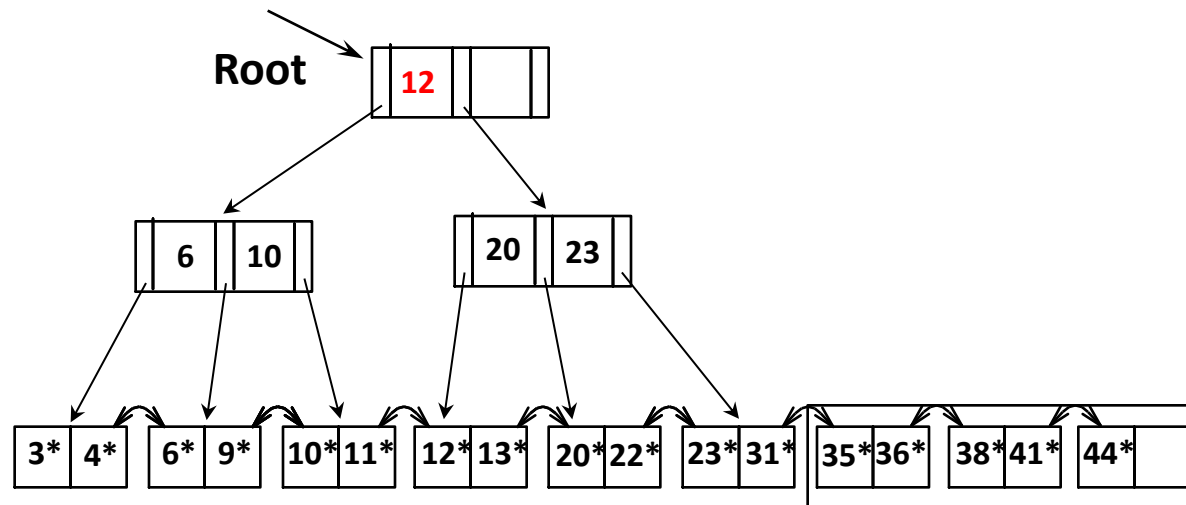
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

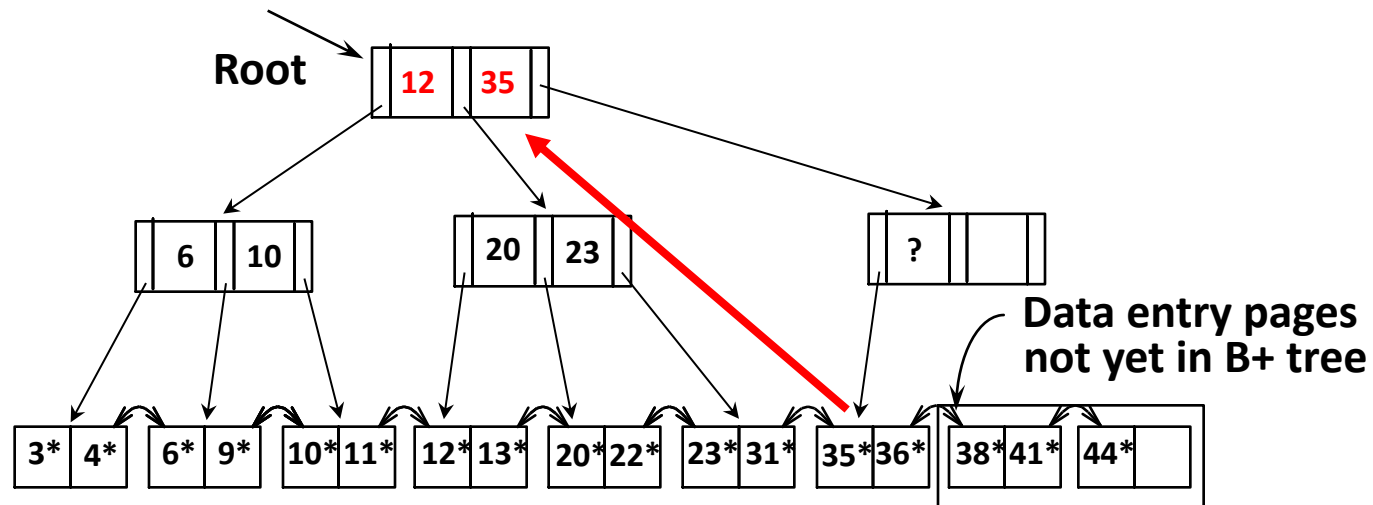
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

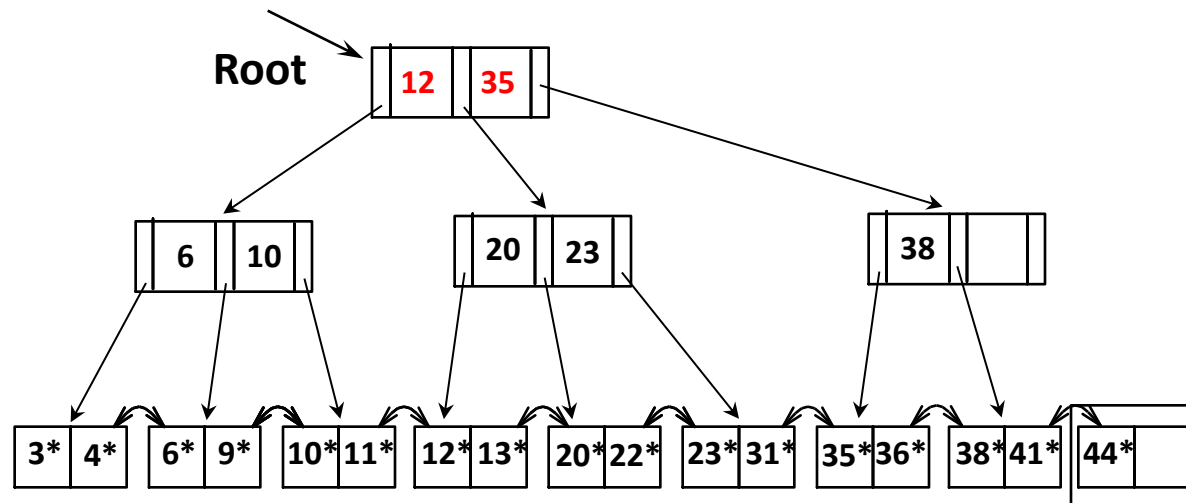
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

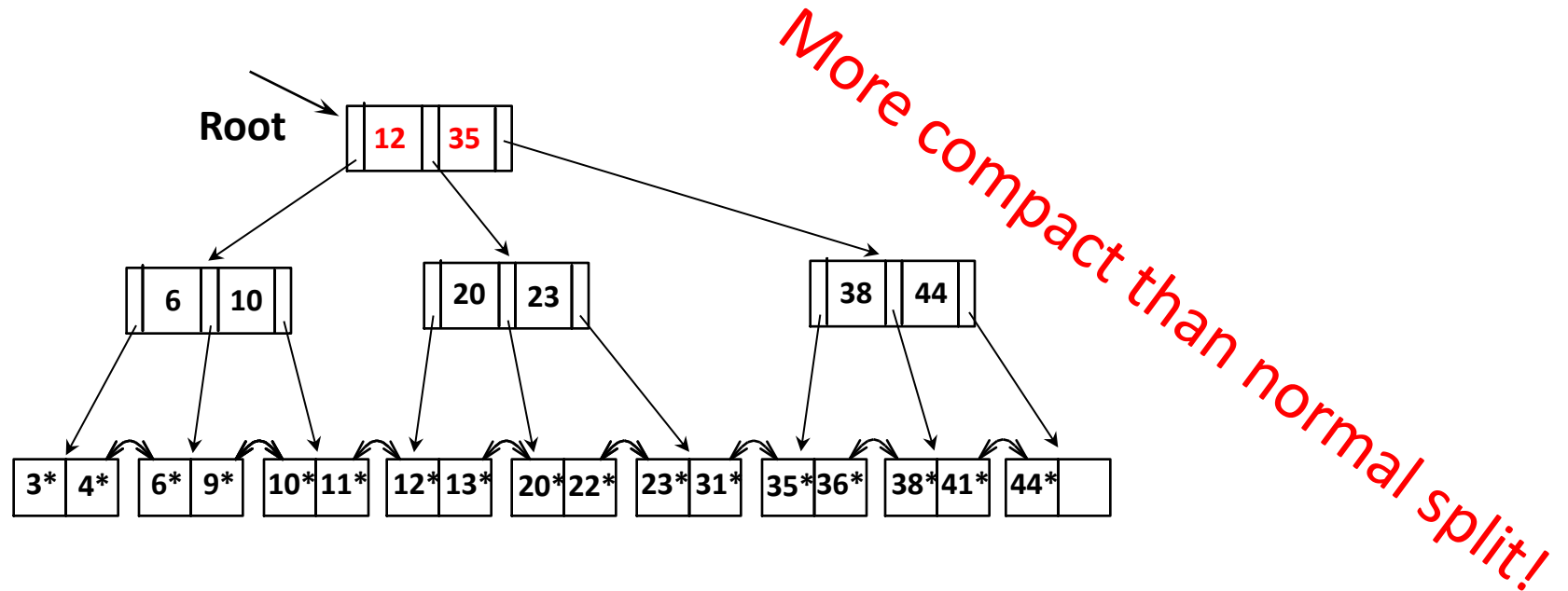
where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Bulk Loading (Change Split Ratio) corrected!

where to insert: into right-most index page just above leaf level
what to insert: the left-most value of the new leaf



what to do when full? when this fills up, create new empty node and propagate a pointer with the leftmost value of the subtree (if needed this may go up right-most path to the root)

Summary of Loading Options

Option 1: multiple inserts.

- Slow.
- Does not give sequential storage of leaves.

Option 2: *Bulk Loading*

- Fewer I/Os during build.
- Leaves will be stored sequentially (and linked, of course).
- Can control “fill factor” on pages.

A Note on “Order”

Order (d) concept **replaced** by physical space criterion in practice (“*at least half-full*”).

- **Index pages** can typically hold many **more entries** than leaf **pages**.
- **Variable sized records** and search keys mean **different nodes will contain different numbers** of entries.
- Even with fixed length fields, multiple records with the same search key value (*duplicates*) can lead to variable-sized data entries (if we use Alternative (3)).

Many real systems are even sloppier than this --- only reclaim space when a page is *completely* empty.

B+ Trees



“It could be said that the world’s information is at our fingertips because of B-trees”

Goetz Graefe

Google (prev. Microsoft, HP Fellow)

ACM Software System Award

Summary

Tree-structured indexes are ideal for range-searches, also good for equality searches.

B+ tree is a dynamic structure.

- Inserts/deletes leave tree height-balanced; $\log_F(N)$ cost.
- High fanout (F) means depth rarely more than 3 or 4.
- Almost always better than maintaining a sorted file.
- Typically, 67% occupancy on average.
- If data entries are data records, splits can change rids!